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Tailorable Remote Unmanned Combat Craft

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

CAPSTONE PROJECT REPORT

TAILORABLE REMOTE UNMANNED COMBAT CRAFT

by

Systems Engineering Analysis Cohort 18, Team B

June 2012

Capstone Project Advisor — Gary Langford
Timothy Chung

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13. ABSTRACT (maximum 200 words)

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The SEA-18B team presents an operational concept for a family of Unmanned Surface Vessels USV) capable of defending ships from asymmetric swarm attacks. This USV, the Tailorable Remote Unmanned Combat Craft (TRUCC), can operate in concert with the next generation of capital surface vessels to combat this critical threat with maximum efficiency.

Critical performance criteria of the TRUCC family were determined through agent-based simulation of a Straits of Hormuz Design Reference Mission. Additional models addressed ship synthesis and operational availability.

A Technology and Capability Roadmap outlines areas of interest for investment and development of the next-generation USV. Interim technology and capability milestones in the Roadmap facilitate incremental USV operational capabilities for missions such as logistics, decoy operations and Mine Warfare.

The TRUCC operational concept fills a critical vulnerability gap. Its employment will reduce combat risk to our most valuable maritime assets: our ships and our Sailors.

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TAILORABLE REMOTE UNMANNED COMBAT CRAFT

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ABSTRACT

U.S. military and civilian vessels are critically vulnerable to asymmetric threats in littoral environments. Common asymmetric weapons such as Anti-Ship Cruise Missiles (ASCM), Low Slow Flying (LSF) aircraft and Fast Attack Craft (FAC) / Fast Inshore Attack Craft (FIAC) threaten U.S. strategic goals and can produce unacceptable losses of men and material.

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LIST OF ACRONYMS AND ABBREVIATIONS

25mm	BUSHMASTER CANNON
50-CAL	50-CALIBER MACHINE GUN
A2AD	ANTI-ACCESS / AREA DENIAL
AEGIS	AUTONOMOUS EXPLORATION FOR GATHERING INCREASED SCIENCE
AIS	AUTOMATIC IDENTIFICATION SYSTEM
Ao	OPERATIONAL AVAILABILITY
AoA	ANALYSIS OF ALTERNATIVES
AOR	AREA OF OPERATIONS
ASCM	ANTI-SHIP CRUISE MISSILE
ASW	ANTI-SUBMARINE WARFARE
AWS	AEGIS WEAPON SYSTEM
B/T	BEAM TO DRAFT RATIO
B/H	BEAM TO HEIGHT RATIO
BOE	BACK OF THE ENVELOPE
C2	COMMAND AND CONTROL
C_b	BLOCK COEFFICIENT
CBR	CHEMICAL BIOLOGICAL RADIOLOGICAL
CG	GUIDED MISSILE CRUISER
CMCC	COMMAND MISSION CONTROL CENTER
COLREGS	INTERNATIONAL REGULATIONS FOR PREVENTING COLLISIONS AT SEA 1972

CONOPS	CONCEPT OF OPERATIONS
CUSV	COMMON UNMANNED SURFACE VEHICLE
DDG	GUIDED MISSILE DESTROYER
DOD	DEPARTMENT OF DEFENSE
DOE	DESIGN OF EXPERIMENT
DRM	DESIGN REFERENCE MISSION
ER	EXTENDED RANGE
ESSM	EVOLVED SEA SPARROW MISSILE
FAC	FAST ATTACK CRAFT
FIAC	FAST INSHORE ATTACK CRAFT
FOB	FORWARD OPERATING BASE
GINA	GLOBAL INFORMATION NETWORK ARCHITECTURE
GPS	GLOBAL POSITIONING SYSTEM
HP	HORSE POWER
HVU	HIGH VALUE UNIT
IED	IMPROVISED EXPLOSIVE DEVICE
INS	INERTIAL NAVIGATION SYSTEM
IR	INFRARED RADIATION
ISR	INTELLIGENCE SURVEILLANCE AND RECONNAISSANCE
J-METL	JOINT MISSION ESSENTIAL TASK LIST
J2EE®	JAVA 2 PLATFORM, ENTERPRISE EDITION
L/B	LENGTH TO BEAM RATIO

LCS	LITTORAL COMBAT SHIP
LSD	DOCK LANDING SHIP
LSF	LOW SLOW FLYER
LT	LONG TON
MANA	MAP AWARE NON-UNIFORM AUTOMATA
MASINT	MEASUREMENT AND SIGNATURE INTELLIGENCE
MBSE	MODEL-BASED SYSTEMS ENGINEERING
ME	MISSION EFFECTIVENESS
MSL	MEAN SEA LEVEL
MV	MISSION VEHICLE
MOE	MEASURE OF EFFECTIVENESS
MOP	MEASURE OF PERFORMANCE
MP	MULTI PURPOSE
NMS	NATIONAL MILITARY STRATEGY
NPS	NAVAL POSTGRADUATE SCHOOL
NSFS	NAVAL SURFACE FIRE SUPPORT
O&S	OPERATIONS AND SUPPORT
OASIS	ORGANIC AIRBORNE AND SURFACE INFLUENCE SWEEP
ONR	OFFICE OF NAVAL RESEARCH
OPN	OTHER PROCUREMENT NAVY
OV	OPERATIONAL VIEW
PC	PATROL CRAFT

Pk	PROBABILITY OF KILL
PM	PROJECT MANAGER
Pssk	SINGLE SHOT PROBABILITY OF KILL
RADAR	RADIO DETECTION AND RANGING
RAM	ROLLING AIRFRAME MISSILE
RCS	RADAR CROSS SECTION
RHIB	RIGID HULL INFLATABLE BOAT
ROE	RULES OF ENGAGEMENT
SE	SYSTEMS ENGINEERING
SEA	SYSTEMS ENGINEERING ANALYSIS
SEP	SYSTEMS ENGINEERING PROCESS
SFC	SPECIFIC FUEL CONSUMPTION
SIGINT	RADARS, SIGNALS INTELLIGENCE
SM	STANDARD MISSILE
SOINN	SELF-ORGANIZING INCREMENTAL NEURAL NETWORK
SONAR	SOUND NAVIGATION AND RANGING
SSBN	BALLISTIC MISSILE SUBMARINE
SSN	ATTACK SUBMARINE
TAD	TEMPORARY ACTIVE DUTY
TG	TASK GROUP
TRUCC	TAILORABLE REMOTE UNMANNED COMBAT CRAFT
UAS	UNMANNED AIRCRAFT SYSTEM

UGV	UNMANNED GROUND VEHICLE
UJTL	UNIVERSAL JOINT TASK LIST
U.S.	UNITED STATES
USAF	UNITED STATES AIR FORCE
USMC	UNITED STATES MARINE CORPS
USV	UNMANNED SURFACE VESSEL
UUV	UNMANNED UNDERWATER VEHICLE
VLS	VERTICAL LAUNCH SYSTEM
VTC	VIDEO TELECONFERENCE

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EXECUTIVE SUMMARY

U.S. military and civilian vessels are critically vulnerable to asymmetric threats in littoral environments. Common asymmetric weapons such as Anti-Ship Cruise Missiles (ASCM), Low Slow Flying (LSF) Aircraft And Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC) threaten U.S. strategic goals and can produce unacceptable losses of men and material. These threats weigh heavily in the strategy calculus for the Anti-Access/Area Denial (A2AD) environment.

The SEA-18B team presents an operational concept and Technology/Capability Roadmap for a family of USVs capable of defending ships from air and surface asymmetric swarm attacks in the littoral domain. By developing the Tailorable Remote Unmanned Combat Craft (TRUCC) in concert with the next generation of capital surface vessels, the TRUCC fleet is shown to be a highly effective force multiplier. The potential employment of TRUCCs provides force protection in choke points, straits and high-threat areas worldwide, allowing manned capital ships to continue critical blue-water missions. Open architecture and common interfaces permit various configurations of the TRUCCs as delineated by a variety of threat mixes regardless of Area of Operations (AOR), and accommodate future sensor, communications and weapons capabilities.

The critical performance criteria of the TRUCC family are determined through Model-Based Systems Engineering (MBSE). Agent-based simulation analysis coupled with a Straits of Hormuz Design Reference Mission (DRM) reveal the most important criteria for TRUCCs in the force protection role. These major design criteria were *force ratio* (number of TRUCCs relative to attackers), *TRUCC weapon Probability of kill* (Pk) and *weapon firing rate*. This output highlighted the important factors for USV development. Large numbers of lower-cost vessels will have more combat capability than a smaller number of larger vessels. Although this concept runs counter to the existing surface ship

development plan, it aligns with the New Navy Fighting Machine concept proposed in 2009. Additionally, the need to have highly capable weapons on smaller ships points to the need for open architecture and common interfaces. This allows for increased weapon (and therefore TRUCC) capability as technology increases. Highly capable weapons on a (relatively) low technology TRUCC platform offer the greatest combat capability against asymmetric threats.

Due to the number of units necessary to carry out missions, Operational Availability (Ao) and reliability are of critical concern for successful TRUCC development. Manned surface combatants achieve Ao numbers of between 20%-60%, and exhibit relatively low reliability. The required size of the TRUCC fleet increases rapidly as Ao decreases, generating the need to focus development of high Ao requirements early in the acquisitions process. Similarly, with no man in the loop to make mid-mission repairs, the TRUCC cannot use the existing surface ship reliability strategy. The loss of assets due to mid-mission failures, with the associated security and tampering issues, is of critical concern. The report proposes use of reliability paradigms from aviation and space industries, because mid-mission system failures are mission critical for USVs.

A Technology and Capability Roadmap outlines areas of interest for investment and development of the next-generation USV using scenario development theory. The key capability milestones necessary for TRUCC development are identified with their attendant technology and policy elements. Design best practices, scalability laws and rational investment theory substantiate interim technology and capability milestones from the Roadmap. Incremental USV operational capabilities in mission areas such as maritime logistics, decoy operations (such as the Advanced Offboard Decoy) and Mine Warfare will serve as stepping-stones to the kinetic and autonomous force protection capability of the TRUCC, but require funding and community interest.

The TRUCC operational concept fills a critical vulnerability gap and its employment will reduce combat risk to our most valuable maritime assets: our ships and personnel.

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The SEA-18B team wishes to thank our friends and families for their support over the nine months required to complete this project. Their understanding and encouragement was critical to the production of this body of work. We truly appreciate the countless of hours of hands-on mentorship provided by our advisors, Gary Langford and Dr. Tim Chung. Their contribution to our education and personal leadership will not soon be forgotten. Additionally, the project team is grateful for the hundreds of man-hours of advice and guidance graciously provided by our stakeholders. Particularly, we would like to thank the following people and organizations:

RADM Rick Williams, Chair of Mine Warfare (RET)
CAPT Jeff Kline, CRUSER director, (RET)
CAPT Trip Barber Deputy Director, OPNAV N81 (RET)
CDR Jim Turner, NECC N9
Chris Marchefsky, ONR Science Advisor to N81
CAPT Carol O'Neal, CRUSER Director for Innovation and Concept Innovation
CAPT Wayne Hughes, NPS Professor of Practice (RET)
Marty Irvine, Ph.D., ONR Science Advisor
Navy Expeditionary Combat Command (NECC) Strategy & Technology (N9)
John R. Lloyd, NPS Distinguished Visiting Professor
CAPT William G. Glenney IV, Deputy Director CNO SSG
Sean Kragelund, NPS Center for Autonomous Vehicle Research
Ken Amster, Naval Air Weapons Station China Lake
Office of Naval Research
Naval Surface Warfare Center – Panama City Division
Naval Surface Warfare Center - Dahlgren
Derek Brown, Global Vigilance Combined Test Force
MAJ Matt Nussbaum, ACC 9
Peter Ateshian, NPS Adjunct Visiting Instructor
Robert Stirbl, Jet Propulsion Laboratory
CDR Douglas Burton, NPS Lecturer, Operations Research
RADM Gerry Ellis, Chair for Undersea Warfare

The project team would like to take this opportunity to highlight the underlying purpose of this study. By developing an operational concept to protect those in harm's way, we hope to minimize the sacrifices of future generations of Naval professionals. Our generation has been particularly impacted by the asymmetric (and unpredictable) warfare of the Global War on Terror. In particular, we recognize those close to us who have given their lives in service to their country.

LT Rob Elortegui
LT Chris Snyder
CAPT Jenn Harris
LCDR Eric Purvis
1/LT Ron Winchester

"Those friends thou hast, and their adoption tried,
Grapple them to thy soul with hoops of steel."
Hamlet, Act I, Scene iii

I. INTRODUCTION

A. PROJECT BACKGROUND

The leadership of NPS's Systems Engineering Analysis (SEA) curriculum generated the tasking statement for this project. In some instances, the SEA team received suggestions for additional guidance from sponsors; at other times, there was sufficient student and advisor capacity to advance the tasking to be of emergent value for the Navy. Numerous Unmanned Surface Vehicle (USV) programs are under development; however, no academically rigorous front-end systems engineering analysis has been conducted to guide a far-reaching, long-term USV technology and capabilities study. Having identified the need for a thorough, comprehensive study a few future integrated manned force structure with USV capabilities, the SEA curriculum distributed the following tasking statement to Systems Engineering Analysis Cohort 18, Team B:

> Design a family of USVs that can be integrated with manned and other unmanned forces to address a broad spectrum of missions. Assess how USVs can be integrated with manned and other unmanned forces to improve Navy (Joint) mission success.
>
> Consider a broad spectrum of missions that:

- Accelerate mission completion (e.g., lethal, non-lethal interactions, Anti-Submarine Warfare (ASW), logistics)
- Change the dynamics and numbers for offense and defense (e.g., swarm or saturation attacks)
- Extend existing capability (e.g., Intelligence Surveillance and Reconnaissance (ISR))
- Reduce risks (e.g., deception)
- Deny access (e.g., Mine Warfare)

1. Scope

The scope of the study focused on USV capabilities and their applications to future military missions. This provided an opportunity to generate a roadmap necessary to implement recommendations along with a validation plan.

2. Project Team

Given the sweeping scope of the project, assembling and organizing a Systems Engineering team was essential to project success. Information management, modeling and simulation, statistical analysis, naval architecture and computer programming were some of the skills required to manage the scope of the project; groups were formed based on the skill sets of the individuals. The core team consisted of six U.S. Naval Officers with over 35 years of operational fleet experience assigned full-time to the Naval Postgraduate School's Systems Engineering Curriculum. The analysis began September 2011.

In January of 2012, 12 additional members from various specialties jointed the core group of six, creating a cross-campus integrated project team. Table 1 represents the varied backgrounds and experiences of these engineering students.

A broad base of experience coupled with cultural diversity, combined with significant real-world experience across a broad spectrum of technical and tactical areas, contributed greatly to the team's analytical process and overall finished product. Figure 1 depicts the SEA-18B team photo on May 8, 2012.

Table 1. SEA-18B Team Listing

Last	First	Rank	Title	Curric	Community / Specialty
Jacobi	Loren	LCDR	Program Manager	SEA	Aviation / WTI / JTAC (10 Years)
Bush	Adam	LT	Lead SE	SEA	Subs Nuclear Engineering (7 Years)
Alexander	Cory	LT	Task Group Lead	SEA	Surface Warfare - Auxiliaries Officer (3 Years) Training and Readiness Officer (2 Years)
Campbell	Rick	LT	Task Group Lead	SEA	Surface Warfare - First Lieutenant (1 Year) Main Propulsion Assistant (1 Year) Fire Control Officer (2 Years)
Edwards	Christien	LT	Task Group Lead	SEA	Surface Warfare - Anti-Submarine Warfare Officer (2 Years) Auxiliaries Officer (2 Years)
Meeks	Matt	LT	Task Group Lead	SEA	Surface Warfare - Assistant Operations Officer (2 Years) Main Propulsion Assistant (2 Years) Communications Officer (2 Years)
Chua	Chee Nam (Chris)		Team Engineer	SE	Singapore Technologies Aerospace Ltd. - UAV Flight Control Field (3 Years)
Diukman	Anner	CPT	Team Engineer	SE	Israeli Defense Forces - Intelligence Directorate Research and Development (6 Years)
Tham	Kine Yin (Jinks)	MAJ	Team Engineer	SE	Republic of Singapore Navy - Surface Warfare Officer - Navigation Officer, Communications Officer, Executive Officer, Staff Officer (14 Years)
Ong	Chin Chuan (Chase)	MAJ	Team Engineer	MOVES	Singapore Armed Forces - Guards Officer (5 Years)
Ding	Sze Yi (Ding)		Team Engineer	Weapons	DSO National Laboratories - Research and Development (4 Years)
Ng	Mei Ling (Vanessa)		Team Engineer	SE	Singapore Defense Science and Technology Agency - Project Engineer (5 Years)
Tan	Szu Hau		Team Engineer	Sensors	Singapore Technologies Aerospace Ltd. - Radar Field (12 Years)
Hagstette	Matt	LT	Team Engineer	Sensors	Information Warfare Officer (3 Years) Nuclear Power Instructor (4 Years) Army Infantry (4 Years)
Yeo	Ing Khang		Team Engineer	Weapons	Singapore Technologies Kinetics Limited - Operations and Support Division (3 Years)
Cher	Hock Hin (Michael)		Team Engineer	Sensors	Singapore Technologies Electronics. - Assistant Principle Engineer (5 Years)
Kwek	Howe Leng	MAJ	Team Engineer	Weapons	Republic of Singapore Air Force - Air Defense (4 Years) Research and Development (5 Years) Project Management (2 Years)
Loke	Yew Kok (Steven)		Team Engineer	Weapons	Singapore Defense Industries - Project Management (5 Years)

Rear: LT Matthew Meeks, Professor Gary Langford, LT Cory Alexander, LCDR Loren Jacobi, LT Christien Edwards, LT Adam Bush, Dr. Timothy Chung

Front: Maj. Kine Yin Tham, Maj. Howe Leng Kwek, Dr. John Lloyd, Mei Ling Ng, Chee Nam Chua, Yew Kok Loke, Ing Khang Yeo, Maj. Chin Chuan Ong, LT Rick Campbell, Cpt. Anner Diukman, LT Matthew Hagstette, Sze Yi Ding, Hok Hin Cher

Not Pictured: Szu Hau Tan

Figure 1. SEA-18B Capstone Team Photo

II. PROBLEM DEVELOPMENT

The given tasking statement granted the team significant latitude to use the principles of Systems Engineering, particularly with regard to developing the problem statement. Ultimately, the team chose a tailored, feedback-driven Waterfall Systems Engineering Process (SEP) model to guide the project progress, depicted in Figure 2.

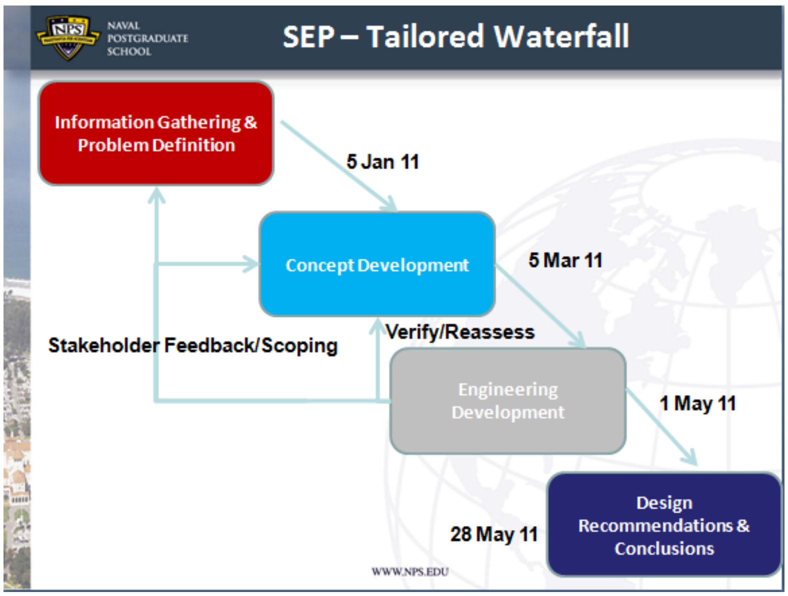

Figure 2. SEP Tailored Waterfall model

With the systems engineering process selected, the team organized for independent mission research into the following Task Groups as seen in Figure 3: (TG – 1) Vessel Escort, (TG – 2) Oil Platform Defense, (TG – 3) Harbor Defense, and (TG – 4) Mine Warfare. Each group consisted of a mission subject matter expert supported by three technical experts. Their findings were presented to the SEA-18B Team in order to discover commonalities between missions.

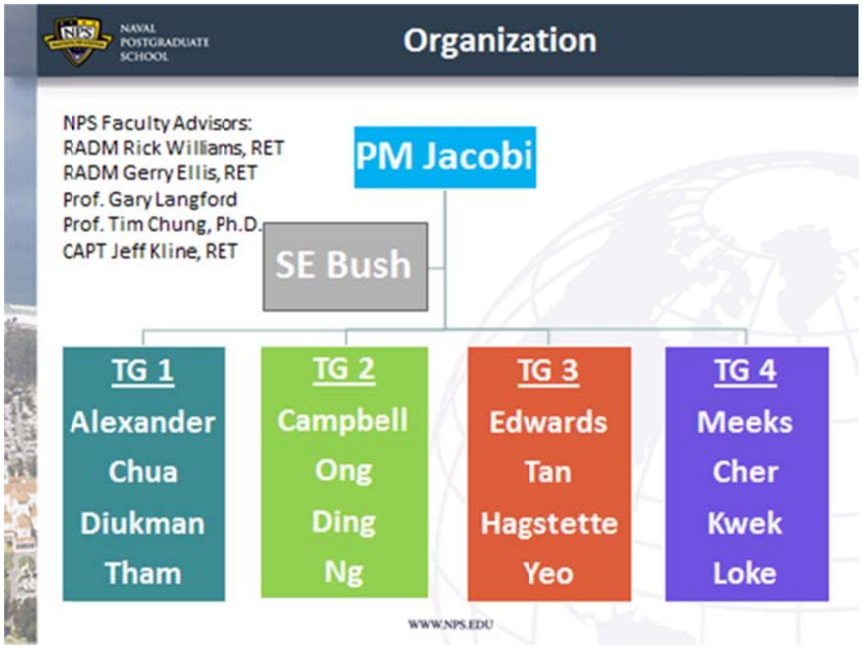

Figure 3. SEA-18B Team Organization

Project development was limited based on the time available to the project team. Figure 4 represents the team's systems engineering process and provides a general idea of when the major systems engineering tasks occurred; however, it does not encompass the full schedule's complexity. The level of effort is normalized for 100% of the team's total effort: this takes into account the increase in team size following the non-SEA students' arrival. Time constraints restricted overall scope to one Design Reference Mission and one iteration of ship's synthesis; however, this timeline is reflective of the project's sequencing.

The Information Gathering and Problem Development stage focused on thoroughly researching the area of unmanned systems to define and understand the assigned problem through stakeholder interviews and historical research. The Concept Development stage incorporated this knowledge to create a Design Reference Mission for future employment of unmanned surface vehicles. The modeling task in Figure 4 represents the engineering development phase of the waterfall process in Figure 2. The modeling task then used this design reference mission to generate a model to analyze and collect data. The writing and report preparation efforts generated a Capability and Technology Roadmap to support the findings of the project and represent the design recommendations and conclusions portion of the waterfall process in Figure 2.

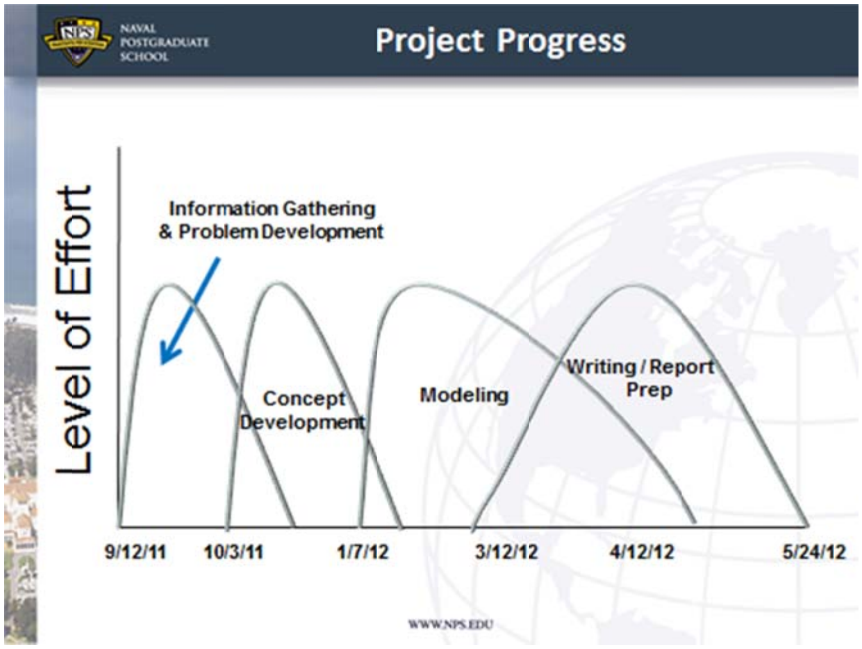

Figure 4. Project Progress

A. INITIAL SCOPING

Early in the SEP, the team investigated all unmanned systems, ranging from aerial to subsurface vehicles, before focusing on the USVs and their attendant maritime mission areas. The team conducted a two-pronged approach to defining the problem for a better understanding of high-level military strategy and associated military mission areas.

By investigating high-level U.S. military strategy, the team conducted a traditional “top-down” analysis. Top-down Systems Engineering Analysis begins with the highest levels of need (in this case national strategy) and retains traceability as the analysis progresses to a level at which the defined problem is solved. The foundation for analyzing future manned force structures is based on the current and projected roles of the U.S. military. Understanding *how* and *why* unmanned systems fit into a future force structure is paramount. Analysis recommending an operational concept for a USV incompatible with U.S. strategy would not satisfy the intent of the project tasking.

Investigation of military mission areas at the core issues of need and problems is reflective of a “bottom-up” analysis. A bottom-up analysis starts with the lowest level of perceived need, and progresses hierarchically to ensure that any solution retains congruity with the high-level requirements. Without a thorough understanding of mission areas, it is impossible to execute an analysis that leads to an effective, deployable operational USV concept. An analysis that produces an operational concept for a USV that is incompatible with the missions and tactics of our forces would have limited utility.

There was a major initial assumption of the (top-down/bottom-up) approach. SEA-18B assumed that most unmanned systems fielded to date were not the result of holistic Systems Engineering analysis. Put another way, the U.S. military (and other militaries, for that matter) are fielding unmanned systems in response to urgent operational needs rather than as a part of a high-level acquisitions plan.[1] The two-pronged review of unmanned system utilization represented the bulk of the problem definition effort. The specifics of the problem definition are described in section (iii) of this report, *Problem Development.*

B. LITERATURE REVIEW

Before making a decision on specific problem within the problem space, SEA-18B conducted a thorough review of available literature in Table 2. The mission subject matter experts read all high-level documents and passed the information along through their leadership role in their TR-groups. Mission-area documentation was divided amongst Task Group Leads, who reported to the SEA-18B team on their assigned areas.

---

[1] (Gansler, 2009, p. 8)

Table 2. Reviewed Literature by SEA-18B Group

Top Down	Bottom Up
The National Military Strategy off the United States of America 2011	Surface Force Training Manual
CNO's Sailing Directions	General Dynamics Robotic Systems
The New Navy Fighting Machine	Decision Support for Network-Centric Command and Control
Quadrennial Defense Review 2010	U.S. Unmanned Aerial Systems
Defense Strategic Guidance	Unmanned Systems Intergrated Roadmap FY 2009-2034
Sustaining U.S. Global Leadership: Priorities for 21st Century Defense	U.S. Navy Maritime Civil Affairs Group Concept of Operations
Joint Operational Access Concept	U.S. Navy Expeditionary Training Command Concept of Operations
National Security Strategy 2010	U.S. Navy Maritime Expeditionary Security Force Concept of Operations
The Future of Unmanned Systems	U.S. Navy Expeditionary Combat Command Force Operational Concept

The top-down documentation in Table 2 led the team to some central strategic and operational themes, as well some important constraints for future military missions. The bottom-up documentation in Table 2 helped identify a method for functionally scoping future military missions. The four main problem domains identified were: (1) defend a known, (2) find an unknown, (3) logistics, and (4) offensive operations/power projection. Based on further stakeholder discussions and SEA-18B technical expertise, the domain selected for detailed investigation was *defend the known*.

C. STAKEHOLDER IDENTIFICATION AND ELICITATION

Given the broad scope of the Information Gathering/Problem Definition stage, the stakeholders involved in this study spanned a broad spectrum of military and civilian specialties. The major stakeholders at Naval Postgraduate School (in Table 3) guided the project studies as well as provided critical feedback throughout the project cycle. This core group provided near-daily feedback to the project team.

Table 3. Major Stakeholders

Last	First	Rank	Specialties
Chung	Timothy	CIV/Ph.D	Robotics Systems Engineering
Ellis	Winford (Jerry)	RADM (Ret)	Undersea Warfare
Langford	Gary	CIV	Systems Engineering
Williams	Rick	RADM (Ret)	Surface Warfare

In keeping with the broad scope chosen for the Problem Development stage, the project team cast a wide net to capture stakeholder inputs. The focus of discussion was the current and future needs of unmanned systems as well as current and perceived future issues in USV development. The natural concentration for an Unmanned Surface Vessel study is easily centered on the U.S. Navy Surface Warfare community and Naval technology developmental agencies, such as the Office of Naval Research (ONR). While these communities provided invaluable feedback to the team, there was a conscious decision to reach beyond the Surface Warfare specialty and the Navy in general. Similarly, identifying stakeholders was not limited only to those involved in unmanned systems. Understanding a wide range of missions, technologies and methodologies paid significant dividends when forming the problem definition. Specifically, the stakeholder discussions highlighted areas within the problem space on which the SEA18B team could have some influence, such as high value unit protection. The stakeholder discussions also identified the areas of the problem space that the team could not influence, like the general acquisition process.

Table 4. Key Stakeholders

Last	First	Rank	Title
Amster	Ken	CIV	Naval Air Weapons Station China Lake
Barber	Arthur (Trip)	CIV SES	Deputy Director Assessment Division (N81)
Canning	John	CIV	G82 Naval Surface Warfare Center Dahlgren
Castelin	Steve	CIV	Senior Systems Engineer, Unmanned Systems Tech NSWC Panama City
Cramer	Megan	Ph.D	PEO LCS S&T Lead
Crute	Daniel	CIV	Head, Modeling and Simulation and Unmanned Systems Technology Div
Crystal	Sargent	LT	NPS Student
Derek	Brown	CIV	Global Vigilance Combined Test Force
Douglas	Barry	CIV	Director Fleet Support & Rapid Prototyping
Dudinsky	John	CIV	Naval Surface Warfare Center - Panama City Division
Elijah	Soto	CIV	Deputy Director Unmanned Systems
Foster	Dave	CiV	Senior Systems Engineer
Garcia	Greg	CIV Ph.D	Naval Surface Warfare Center - Panama City Division
Heermann	Philip	CIV Ph.D	Senior Manager for intel Systems, Robotics & Cybernetics, Sandia Nat. Labs
Horner	Douglas	CAPT/ Ret	Naval Post Graduate School Unmanned Systems Lab
Hughes	Wayne	CAPT (RET)	NPS Senior Lecturer
Ivy	Robert (Bob)	CIV	Maritime Systems at General Dynamics Robotic Systems
Joeseph	Douglas	CIV	Net-Centric Warfare Analysis
Kimmel	Rich	CIV	MIW Requirements N8 for NMAWC
Kragelund	Sean	CIV	Naval Post Graduate School Unmanned Systems Lab
Kucik	Daniel	CIV Ph.D	Naval Surface Warfare Center - Panama City Division
Marchefsky	Christopher	CIV	ONR Science Advisor to OPNAV N81
Matos	Tony	LCDR	PEO Ships (SEA 21)
Nussbaum	Matthew	MAJ	ACC 9 OG/OGV
Sanzero	Sandy	CIV Ph.D	Manager for intel Systems, Robotics & Cybernetics, Sandia Nat. Labs
Shafter	Dustin	CIV	Network Analyst
Smith	Thomas	CAPT	Commanding Officer, Naval EOD Technology Division
Steadley	Scott	CAPT	Military Deputy (Code 7005) Ocean & Atmospheric S&T NRL
Stewart	Andrew	CIV Ph.D	Ocean Engineer for APL UW
Stirbl	Robert (Bob)	CIV Ph.D	Program Manager, Navy, Marines, and other DoD agencies JPL
Tree	Andrew	CIV	Head, Weapons Environments & Simulation Branch
Turner	Jim (JT)	CDR	NECC Assistant COS Strategy and Technology
Ward	Robert (Bob)	CIV (Phd)	OPNAV N81 Scientific Analyst
Warren	Nick	CAPT / USMC	White House Military Office

Many stakeholders contributed in minor ways to the project; however, Table 4 lists those who provided substantive input into the Systems Engineering Process. Each of these individuals contributed their time to the elicitation process. Many stakeholders participated in multiple interview sessions, including Video Teleconferences (VTC) and Temporary Active Duty (TAD) trips. In all, the Tailorable Remote Unmanned Combat Craft (TRUCC) project team conducted over 100 stakeholder interviews during this process. For example, the discussions with John Dudinsky from Naval Surface Warfare Command Panama City highlighted the importance of interoperability between unmanned systems.

In addition to the stakeholders listed, the team engaged various stakeholders by attending community conferences of interest. These included the:

- Surface Navy Symposium 10–12 JAN 2012
- Association for Unmanned Vehicle Systems International Program Review 7–9 FEB 2012
- ONR Unmanned Maritime Systems Conference 30–JAN–2012 through 2–FEB–2012

Attendance at these conferences increased the team's understanding of current and future needs impacting unmanned systems. Taking advantage of the opportunity to interact with the various communities resulted in an increased understanding of the tasking statement. Common themes from the conferences were the need for cooperative inter-community development, and increased standardization of manned / unmanned system interfaces.

III. NEEDS ANALYSIS

Unmanned Surface Vehicles can provide combat capability and increase efficiency (in terms of Operations and Support (O&S) costs) only when the correct system is paired with the correct mission. A thorough Systems Engineering Analysis of this problem required connecting and coupling high-level strategy with low-level tactical employment as well as analyzing the appropriateness of the technical requirements for unmanned systems to support and augment manned systems. The appropriateness of this understanding, when applied to the initial tasking statement, led to the underlying problem statement for this project. In summary, the problem is as follows: current USV analysis provides only short-term guidance; manned vessel procurement hangs on long-term, front-end, analysis of capabilities and threats. To define a manned-unmanned mix for the future, a similar long-term analysis is required for unmanned systems.

A. WHY UNMANNED SYSTEMS?

Unmanned systems are expensive to develop and can involve high levels of technical risk when implemented in a short time frame.[2] They can also result in high O&S costs due to system complexity and/or system immaturity. Heretofore, urgent operational needs have driven the development of unmanned systems.[3] The effects of the high demand were particularly evident in the dramatic and rapid increase of unmanned air systems (UAS) executing ISR missions in the Global War on Terror. Similarly, counter-Improvised Explosive Device (IED) operators employed dozens of different Unmanned Ground Vehicles (UGVs) as they grappled with the IED problem in Iraq.

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[2] (Winnefield & Kendall, 2010, p. 42)

[3] (Gansler, 2009, p. 8)

Beyond urgent operational needs, there is a need for unmanned systems in the long-term force structure of the armed forces. The coupling of increased operational risk with decreasing budgets places a high priority on achieving efficient combat capability, minimizing the threats to personnel, and vital equipment. As budgets decrease, a mix of manned and unmanned systems will confront threat countries who are "rapidly acquiring technologies, such as missiles and autonomous and remotely-piloted platforms that challenge our ability to project power from the global commons and increase our operational risk."[4] Providing sufficient analysis to allow decision makers to define the optimum mix of manned and unmanned systems is at the very heart of this study.

B. MISSION CATEGORIZATION PROCESS

The first step in identifying missions for which USVs add value in terms of lower cost and risk involved identifying the full range of missions executed by the Department of Defense (DOD). Given the broad scope of the project tasking, the project team did not initially limit investigation to maritime missions. Using the knowledge gained during the Information Gathering phase (spanning Air force, Army, Navy, and Marine Corps, as well as contractors, researchers, and test range operators), in addition to organic operational experience, the project team identified the major missions of the U.S. military and their associated sub-missions. While simple in theory, community and service definitions of mission areas complicated this process. For example, the term "air defense" has many different meanings to different services. Effectively categorizing missions required a significant level of taxonomy development, associative matching, and correlative comparisons; a small portion is shown in Figure 5.

[4] (Obama, 2010, p. 12)

Figure 5. Mission Categorization Attempt

Ultimately, the Systems Engineering Process, guided by stakeholder feedback and documents, such as the Universal Joint Task List (UJTL) and Joint Mission Essential Task List (J-METL), led to development of 17 overall mission areas, supported by 74 associated sub-missions (see Appendix I). After missions were identified, the project team analyzed each mission area to match the tasking statement scope with specific missions. Basic questions were posed to further this effort. These questions included:

- Would an unmanned system prevent a human from being harmed?
- Would an unmanned system perform the task better than a human?
- Does the unmanned system perform a task that a human can not?

These questions attempted to codify the benefits of an unmanned system in each mission. The answers to these questions resulted in a set of rules by which the differences between manned and unmanned systems could be assessed. Unfortunately, basic rule sets alone were too simplistic to guide a decision on manned vs. unmanned systems.

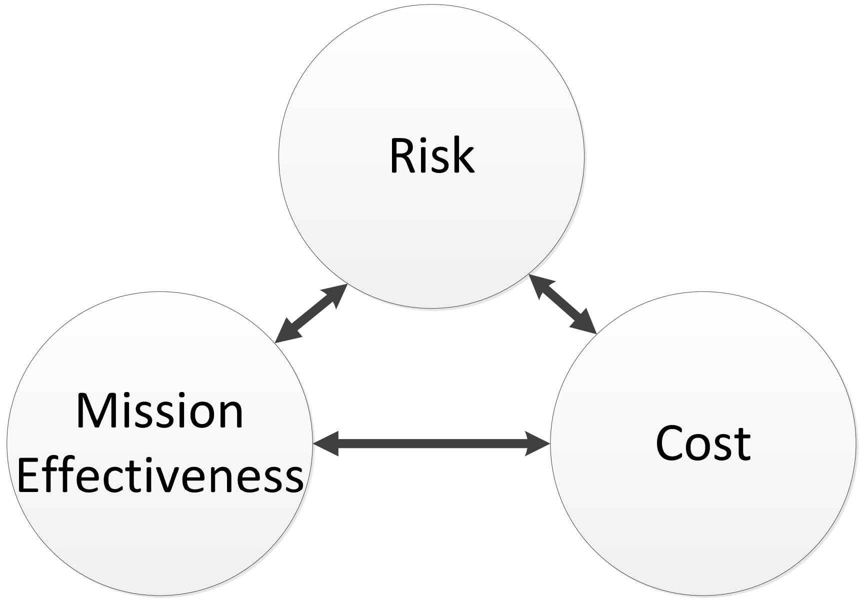

Figure 6. Intersection of Trade Space

The normal trade space for the acquisition of any system is cost, schedule and performance.[5] The project team assumed that sufficient time was available to accommodate the technology integration required for unmanned system employment, so the schedule variable was not considered in the analysis trade space. Unmanned system capability exists within the trade space of risk, cost, and mission effectiveness, shown in Figure 6. Risk, in this context, is defined as risk of loss of life or injury. One of the main advantages of unmanned systems is the ability keep personnel out of harm's way. Mission performance is the ability of the system to complete a mission based on the measures of effectiveness. Cost spans the full life cycle cost of the system. It is important to note that this analysis does not conduct a full life cycle cost analysis for the TRUCC. That cost estimation is open for further study. The cost analysis in this report was limited to rough order of magnitude procurement cost. As unmanned systems become a potential tool toward mission accomplishment, this trade space dominates the essential decision criteria facing the DOD. An in-depth understanding of these

[5] (Rendon & Snider, 2008, p. 5)

compromises becomes particularly important in a resource-limited environment. Purchasing unmanned systems because they can perform a mission does not guarantee combat efficiency. Simply put, just because a USV is capable of conducting a particular mission, it does not mean it necessarily should. If the unmanned system cannot achieve sufficient mission effectiveness, does not result in decreased risk, or system cost increases, then the manned system is the better choice. This essential trade space should be at the forefront when discussing unmanned systems integration. In the words of Keith Bontrager, "Strong. Light. Cheap. Pick any two."[6] Unmanned systems are not the panacea for all the DOD's budgeting, risk mitigation, and combat effectiveness problems; however, an effective manned / unmanned mix can provide an efficient, highly effective force. This report provides quantitative analysis to assist in decisions regarding what missions USVs should do, and the areas of USV design that drive mission success. The systems engineering process is particularly well suited to further this effort as it balances the needs of the stakeholders with the boundaries set by the system.

[6] (BONTRAGER, 2011, p. 1)

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IV. PROBLEM STATEMENT

Current unmanned systems analysis is insufficient to propel the development and integration of unmanned systems into future force structure decisions. Studies to date have generally been limited in scope to five years or less. This method of analysis contrasts sharply with the 30-year shipbuilding plan that offers a holistic approach to shipbuilding building based on strategic priorities and budget realities.[7] Interestingly the 30-year shipbuilding plan considers only manned vessels, although unmanned systems are relatively inexpensive, relatively easy to build, and have shorter lifecycles than capital ships. Given the dramatic impact of unmanned systems, particularly UASs, in the Global War on Terror, it is reasonable to assume that unmanned systems will influence the manned force structure during the next 30 years.

There are significant hurdles associated with identifying the right mission areas of which to apply unmanned systems to gain maximum combat efficiency. Technology development and policy guidance for unmanned systems are potential barriers to integrating these force multipliers into the long-term force structure. The project team used needs analysis to identify a capability gaps suited to USVs. Gaps are defined as deficiencies in operational or use concepts, current or projected operational or utility disadvantages, technologies, or misunderstood future needs.[8] Many potential gaps were identified; however, the most stressing was Multi-Threat Force Protection.

Each gap in Figure 7 is associated with a Design Reference Mission (DRM). A Design Reference Mission defines a specific projected threat and operating environment baseline for a given force element, which range from a single-purpose weapons system, to a multi-mission platform, or system of

[7] (Director, Warfare Integration (OPNAV N8F), 2011, p. 21)

[8] (Langford, Foundations of Value Based Gap Analysis: Commercial and Military Developments, 2009, p. 2)

systems.[9] Each DRM can have one or more has either an Unmanned System solution, a Manned System solution, or a Non-Material solution. For example, the Anti-Ship Cruise Missile DRM has potential solutions in each solution realm; a USV satisfies the unmanned approach, employing DDGs/CGs satisfies the manned approach, and developing new tactics satisfies the non-material approach. By direction, the SEA-18B team explored the problem with the intent of finding a solution for the Multi-Threat Force Protection gap by employing an unmanned surface vehicle.

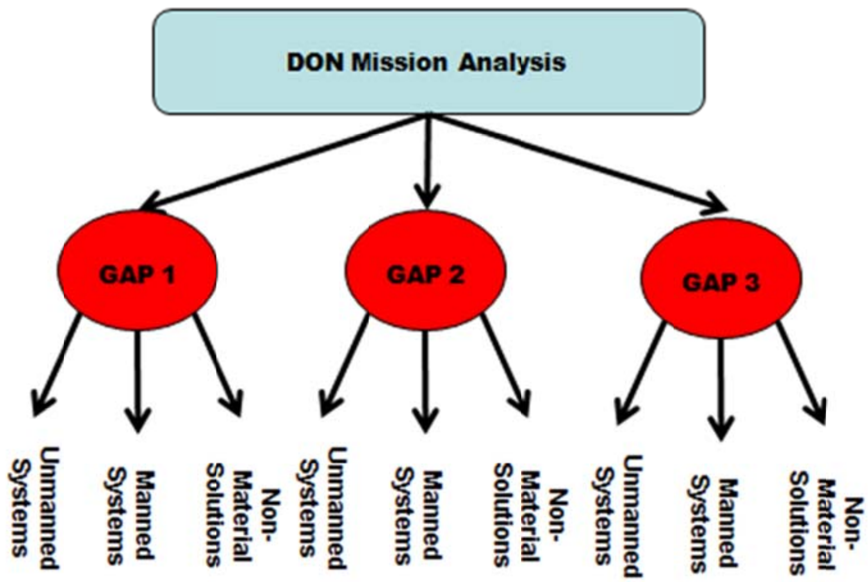

Figure 7. Department of the Navy Mission Analysis

A. LONG-TERM ANALYSIS – WHY THE LONG LOOK?

Conducting long-term analysis of combat operations is inherently challenging due to the possible introduction of disruptive technologies; however, long-term analysis is critical to all force structure decisions and is at the heart of the problem statement. The Guided Missile Destroyer (DDG-51) replacement

9 (Lilly & Russell, 2003, p. 257)

(not yet named) is scheduled to begin construction in 2031 and to combat threats through 2060 and beyond.[10] Given the long lead-time of these ships, requirements analysis based on long-term analysis of future threats is incumbent in manned ship construction. Applying the same long-term, high-level analytical process will prevent costly overruns and duplicity. Long-lead planning is a best practice.[11] The Air Force's Global Hawk was intended to duplicate some capabilities of the manned U-2. Instead of returning better mission effectiveness the unmanned system proved less capable and more costly.[12] Programmatic failures are bound to happen; no analysis can prevent all technological or cost failures in the acquisitions process; however, a thorough, long-term analysis that examines a true manned / unmanned surface ship mix will minimize the cost and capability implications of these failures. Inadequate USV analysis limits progress towards achieving unmanned capability and will force the Navy to continue its tradition of a manned surface fleet into the foreseeable future.

B. FUNCTIONAL MISSION BREAKDOWN

Attempting to predict the future of warfare was beyond the scope of this project; however, an analytical method of examining future missions was required to anchor this report in a bounded, future realism. Developing an analysis for the 17 missions and 74 sub-missions (see Appendix I) identified during early stages of the project would have been cumbersome at best. Therefore, the project team applied the Systems Engineering approach to categorize mission sets in terms of capabilities. By taking a *functional* approach, four broad categories of missions emerged.

C. FUNCTIONAL MISSION DEFINITIONS

Listed are the functional mission category definitions.

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10 (Deputy Chief of Naval Operations (N8), 2012, p. 16).

11 (Sullivan & Pickup, 2006, p. 1)

12 (Schogol, 2012, p. 1)

1. Defend a Known (The Process)

Operations conducted to prevent unwanted influence on designated friendly or neutral assets. Generally, this functional area encompasses missions such as force protection, escort missions and anti-surface warfare. These operations can protect moving or stationary assets against the full range of enemy influence, from kinetic strikes to electromagnetic interference and monitoring.

2. Find an Unknown (The Process)

Operations conducted to locate, identify and characterize an object of interest. This functional area encompasses missions such as Intelligence, Surveillance and Reconnaissance and mine sweeping. The purpose of these missions can vary across the spectrum of military influence. An object, once localized, may be acted on (kinetically or otherwise) immediately, at some future point, or simply tracked for situational awareness.

3. Logistics (The Process)

Operations conducted to move personnel, equipment or materiel to or from an area of interest. This functional area encompasses missions such as amphibious ship-to-shore movement, overland convoy operations and trans-oceanic transportation. The purpose of these missions is ultimately to connect logistics and operational nodes.

4. Offensive Operations / Power Projection (The Process)

Operations conducted to actively influence an object of importance. This functional area encompasses missions such as long-range strike, naval surface fire support and close air support. The purpose of these missions is to actively strike enemy assets at the time and place of the attacker’s choosing.

The last mission is assumed to be primarily in the realm of ground forces, or those supporting ground operations. With the concurrence of project advisors, the research was scoped to the first three functional mission categories.

D. FUNCTIONAL MISSION COMPARISON

For validation, the four functional mission categories were compared to the functions presented in the 2009 study completed at NPS titled *The New Navy Fighting Machine*.[13] This document examined a hypothetical future force structure comprised of a larger number of less-capable, specialized vessels than utilized today. To that end, the authors of *The New Navy Fighting Machine* conducted a similar functional grouping of missions. These functions were:

- Safeguard the movement of goods and services at sea
- Deny enemy movement
- Deliver goods and services from the sea
- Prevent enemy delivery to our shores

These functional categories were slightly different from those mentioned previously; however, they encompass similar concepts. The functional mission area "Safeguard the movement of goods and services at sea" has a strong correlation to "Protect the Knowns." Additionally, "Delivery of goods and services from the sea" correlates to "Logistics." The last functional category "Prevent Enemy Delivery to our shores" correlates to "Offensive Operations/Power Projection"; however, the point of view is different. The SEA-18B function assumes that the U.S. military will be executing offensive operations; the *New Navy Fighting Machine* authors assumed that prevention of offensive operations by others is the ultimate goal. Another key difference was that the *New Navy Fighting Machine* assumes there are no unmanned surface vehicles in the fleet. The related missions are summarized in Figure 8.

[13] (Hughes Jr, 2009, p. 24)

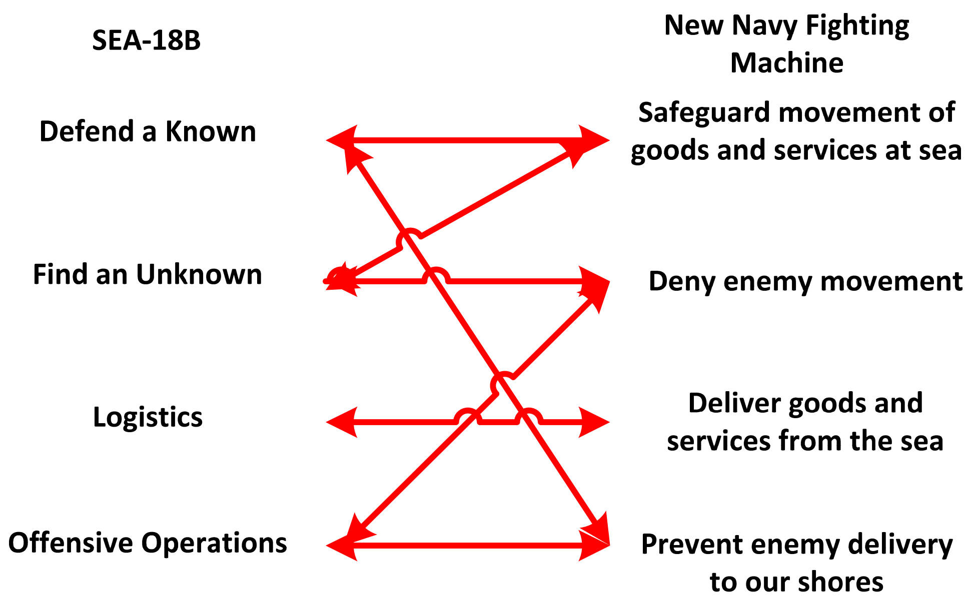

Figure 8. Mission Relations

E. FUNTIONAL MISSION UTILITY

Classifying missions by broad function allowed the maximum utility and flexibility for the analysis of future missions. In broad terms, the missions of the military were categorized using these definitions. Future missions will have different tactics, better sensors, and harder-to-find targets, but the four main functional categories remain.

It was not the goal of the project team to assign import to any specific threat system or weapon, but rather to examine the sensitivities of functional missions to military capabilities. The analysis process allowed the comparison of different USV configurations. For example, the comparison of vessels with high speeds to those with slower speeds to determine which best accomplished the functional mission of “Defending the Knowns.” Divorcing the missions from specific mission equipment allowed just such a capability-based assessment. For example, the missile firing rate in a particular scenario was not defined by a specific weapons system, such as the Rolling Airframe Missile.

Designing a system-of-systems to exploit the capabilities highlighted in this study remains for future detail design; however, the importance of these capabilities cannot be overstated. Identifying the capabilities that influence a functional mission area gives analytical weight to the types of long-term force structure decisions that will drive efficiency in the acquisitions process.

F. DESIGN REFERENCE MISSIONS

The project team developed four discrete Design Reference Missions to relate these functional categories to missions. The creation of specific DRMs was an essential step in revealing the key design factors of unmanned surface vehicles. The specific environmental factors described in each DRM allowed the project team to develop the assumptions required for modeling and simulation.

- DRM 1: Logistics
- DRM 2: Decoy Operations
- DRM 3: Mine Sweeping
- DRM 4: Multi-Threat Force Protection

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V. DESIGN REFERENCE MISSIONS

The Design Reference Missions were scoped to littoral missions, commonly referred to as “brown-water” and “green-water” missions. “Blue-water” operations were not investigated. These missions have traditionally been the domain of manned U.S. Navy Capital ships; only in recent years have littoral missions resurfaced, particularly with the foundation of riverine squadrons and the Naval Expeditionary Combatant Command. While no commonly-accepted, cross-community definitions of brown water and green water exist, they are conceptually distinct from blue water missions. By common convention, blue-water missions imply long-duration, open-ocean deployments. Brown-and-green water missions imply missions close to shore.

USVs are uniquely appropriate for littoral operations for many reasons. First, the littoral Concept of Operations (CONOPS) are still developing, making it easier to integrate new technologies. The cost of building and trying something in an environment marked by change is less than with existing technology. Secondly, the extensive manpower infrastructure geared to support blue-water missions is slow to change. Using unmanned systems in the littoral environments can minimize the changes required to support the increased presence in these areas. Additionally the Surface Warfare community is well vested in multi-role manned capital ship construction. Absent major disruptive changes to the 30-Year Shipbuilding Plan, the large multi-role capital ship will continue to dominate blue-water missions. Lastly, even highly reliable USVs will experience failures that require manned repair processes. Manned ships on long blue-water deployments can conduct mid-cruise repairs using existing ships’ crews. Unmanned ships experiencing similar failures on long deployments may require intervention that is much more extensive. Getting repair or recovery teams to distant failed USVs represents a much greater challenge for blue-water operations than to those in the littorals. Highly reliable platforms mitigate the risk of mid-mission failures on long deployments; however, this could be costprohibitive particularly given that the technology for USVs has yet to be operationally fielded. For these reasons, the DRMs chosen for this analysis were restricted to littoral operations.

The analytical process used herein could apply to blue water operations; however, some underlying assumptions would likely change, thereby influencing the analytical results. For example, sensor range could conceivably become a driving sensitivity factor in a blue-water modeling environment.

A. LOGISTICS DRM

Generally speaking, logistics missions are efficiently executed by manned vessels. Large ocean-going civilian maritime vessels typically have crews of between 20 and 40 personnel. Even the military's Landing Craft Utility has a crew of only 10. Despite this efficiency, there are many reasons why an USV might be used for the transportation of goods and personnel. High-threat environments, such as resupplying embattled Marines in a remote location, or high-risk environments, such as those involving Chemical Biological Radiological (CBR) threats, are natural areas for USV employment for logistics missions. Additionally, a TRUCC configured for logistics could serve as a springboard for technology development benefiting other mission areas.

In order to achieve this goal, the USV must be able to execute waypoint navigation and deal with obstructions and conditions along the way. Above-water obstructions such as other vessels, landmass and floating surface clutter represent only part of the navigation problem for an USV. Submerged objects, sand bars and shoals are additional obstacles that a USV may be required to deal with reliably. Ultimately, these tasks need to be executed reliably enough to comply with international maritime law, specifically the International Regulations for Preventing Collisions at Sea (COLREGS). Lastly, sufficient reliable two-way communication structures must exist to support USV tracking, mid-mission re-direction and fault monitoring.

Several communities can benefit from technology necessary to support the logistics Design Reference Mission. The United States Marine Corps (USMC) and amphibious Navy could execute efficient ship-to-shore movements with a logistics USV. The Surface Warfare community and the Military Sealift Command could use these for their respective logistics missions.

It is important to note that all of the technologies necessary to support the logistics DRM currently exist, but they are not fully integrated into a cohesive system. The maritime environment requires situational awareness both on and below the water. Demonstrating the reliability of such a navigation system and certifying its use for the global maritime environment would contribute significantly to the time required for initial operational capability.

B. DECOY TRANSPORTATION DRM

The second DRM was transportation of decoy systems, such as the Advanced Offboard Decoy. The technology required for this DRM is consistent with the Logistics DRM; however, it is distinct because it represents a non-kinetic option for the "Protect the Knowns" mission category. Generically, decoy systems attract enemy weapon systems. Using unmanned systems in this DRM reduces risk to manned vessels; the weapons would target the unmanned ships and/or their decoys rather than manned vessels. The TRUCC could deploy with a decoy and execute waypoint navigation in a manner representative of High Value Unit (HVU) patrol, such as an aircraft carrier deployment. Alternatively, the decoy-carrying TRUCC could maintain station on a HVU, but maintain a 100 nautical mile separation, causing an enemy to believe the deployed force was larger than actual.

The same requirements exist for this DRM as for logistics, with the potential capability to maintain station on a command unit, such as a HVU. The requisite technology already exists, and its integration into this DRM has relatively low technological risk.

The Surface Warfare Community, USMC, and the amphibious Navy are the primary communities of interest for this DRM.

This capability should be developed in concert with the Logistics DRM as they share essentially the same technology.

C. MINE WARFARE DRM

To support Mine Warfare in this DRM, the USV would not execute Mine Warfare itself, but rather transport, deploy, and recover Mine Warfare equipment. Most of today's Mine Warfare system-of-systems use a similar concept; the Mine Warfare equipment operates independent of the host vehicle moving it through the water. For example, the prime mover could be a helicopter or a surface ship. The function of the mission equipment is completely independent of the towing platform for functions other than movement. Some examples of sonar equipment operating independently are the AQS-20 Mine Hunting Sonar and the ALQ-220 Organic Airborne and Surface Influence Sweep (OASIS) and Single-Pass Detect-to-Engage. The Single-Pass Detect-to-Engage system, notably, is in its conceptual infancy, but could be engineered to work within this DRM.

To conduct this mission, the USV would require the capabilities from the previous DRMs. The USV would transport Mine Warfare equipment around the battlespace as directed by the Mine Warfare commander, and as dictated by the ranges and deployment envelopes of the Mine Warfare systems. The USV would have to interact with mission equipment not present in the previous DRMs. The interaction with mission equipment requires open architecture and common interfaces to maximize system utility. Open architecture and common interfaces are at the heart of a multi-role Mine Warfare USV, because the USV would not be limited to a single Mine Warfare system. In one configuration, the USV could be used for mine sweeping, then reconfigured for mine hunting, using mission equipment from two different contractors. If open architecture and common interfaces are mandated in the requirements stage of both the USV and the Mine Warfare systems, this DRM could become a reality.

The primary communities of interest are the Mine Warfare community and the Surface Navy.

Because of the difficulties involved in specifying, standardizing, and developing open architecture and common interfaces, the Mine Warfare capability would take significantly longer to develop than the Logistics and Decoy capabilities.

D. MULTI-THREAT FORCE PROTECTION DRM

In this DRM, the USV protects friendly ships from high-density swarm threats as they operate in high threat littoral areas by detecting, classifying, and engaging threat systems.

The USV requires all the capabilities discussed thus far: waypoint navigation, obstruction avoidance, COLREGs compliance, two-way communications, maintaining position on a HVU, open architecture, and common interfaces. Additionally, the USV must have a high level of cognitive capability. Theater Rules of Engagement (ROE) cannot be cover all contingencies; they are heuristics that apply to a tactical scenario. In today's tactical situations, a human combines understanding of the ROE with situational awareness and makes life-or-death decisions. In order to achieve the Multi-Threat Force Protection DRM, the USV needs a level of cognition similar to that of a human decision maker in order to make tactical risk assessments leading to weapons release for situations not explicitly defined in the ROE.

The USV will conceivably operate in various modes of independence. At the highest level of independence, a USV will operate completely autonomously, with no human intervention. In conservative modes, a human operator will control a network of USVs. An efficient interface between man and machine is necessary to ensure DRM success, because swarms of threats can easily overwhelm a human controlling large numbers of USVs. The consequence is time delays associated with increased human-processing rendering the USVs unable to conduct their force protection mission.

The primary community of interest for the Multi-Threat Force Protection DRM is the Surface Warfare Community; however, the technology described for this DRM has the potential to influence the UAS and Unmanned Underwater Vehicle (UUV) communities.

The high-level cognitive capability development timeline represents the longest lead-time development cycle, because of the associated programming complexity, processing speeds, and policy issues.

E. OPERATIONAL CONCEPT DEVELOPMENT

This family of USVs is capable of operating across a wide range of mission areas using configurable weapons, sensors and communications equipment. Depending on the level of technical maturity, mission type, and control required, the TRUCC could operate via remote control (i.e. one operator to one USV), operate fully independently (full autonomy) or using a combination of these two extremes. For example, the USV may transit independently to an area of interest, then alert an operator when the terminal area is reached. Alternatively, a swarm of TRUCCs could work collectively to defend a high value unit from attack. A single person (or small group of people) could control a swarm operating collectively. Depending on the ROE, the TRUCCs could alert the operator that a target had been identified for engagement; the operator would then consent to weapons release. These two examples of operating independently and collectively show different ways in which the TRUCC could incorporate various levels of autonomy ("sliding autonomy") to reduce the reliance on manned control stations. Given time, research, and operational employment-inspired development, sliding autonomy would increase and move closer to independent and autonomous capabilities. Commensurately, the operational concept would evolve to include the processes supportive of autonomous, semi-autonomous, and tethered operations.

F. TRUCC SHIP SYNTHESIS

The Mission Vehicle team conducted ship synthesis on three types of TRUCC hull forms to execute the DRMs. Ship synthesis provides early stage vessel development, rooted in naval architecture principles. The vessels within each group have a range of sizes to facilitate integrated modeling analysis with the other modeling groups. The Mission Vehicle team selected three ranges of vessel sizes by analyzing possible deployment methods. The vessels were not limited to the proposed deployment methods and served as a starting point for this analysis. Ship synthesis provided three points (small, medium, large) in a solution space to conduct analysis.

1. Small

The Small TRUCC length ranges from 7 to 36 feet. This size vessel has the capability to be directly deployed via a boat davit. This deployment method leverages existing infrastructure and deployment techniques currently in place on today’s surface combatants; most Navy ships would have the capability to launch and recover a Small TRUCC using existing shipboard equipment. The Small TRUCC ranges in size from a small Rigid Hull Inflatable Boat (RHIB) to that of a Dauntless-class patrol craft, as shown on the left size of Figure 9.

Figure 9. USV Model-Small (7–36 feet)

2. Medium

The Medium TRUCC length ranges from 37–90 feet. This size of vessel could be transported in the welldeck of a modern amphibious ship, such as a Dock Landing Ship (LSD). Two vessels of this size could be stored fore-and-aft within the welldeck, leveraging existing amphibious ship transportation capabilities. This TRUCC size equates to the approximate size and displacement of a MK V patrol craft as shown in the upper left of Figure 10.

Figure 10. USV Model- Medium (36–90 feet)

3. Large

The Large TRUCC ranges in length from 91–200 feet. A vessel of this size would most likely transit independently to an Area of Responsibility (AOR), or be delivered via maritime prepositioning assets. A TRUCC this size allows the use of long-range weapons. This vessel is approximately the same size and displacement as a Cyclone-class coastal patrol craft as shown in the upper left of Figure 11.

Figure 11. USV Model-Large (91–200 feet)

The three design points (small, medium, large) where ship synthesis was used covers the main deployment methods used today.

G. TRUCC EMPLOYMENT CONCEPT – FORCE PROTECTION DRM

Given the scope of the project, including the schedule and manpower limits, the Force Protection DRM was selected for further development. The Force Protection DRM represents the most efficient use of project team resources and encompasses technology and capabilities required for the other DRMs. Focusing on the most complex DRM allowed analysis of many of the aspects of the other DRMs. There are, of course, opportunities to further develop aspects of the other DRMs, such as the on-load/off-load issues for the Logistics DRM. Issues specific to the other DRMs remain for further exploration by follow-on efforts.

In the Force Protection DRM, the TRUCCs deploy as a team to protect a HVU. This DRM allows the TRUCCs to leverage local and over-the-horizon networking capability to cooperatively engage incoming threats as shown in the Operational View 1 (OV-1) diagram in Figure 12.

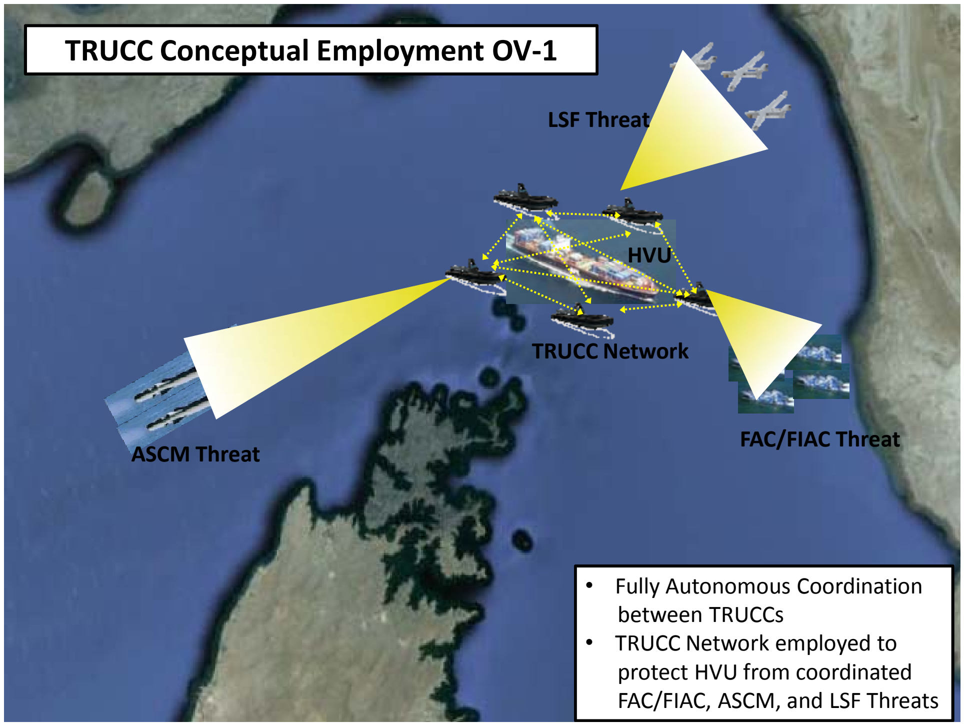

Figure 12. TRUCC Conceptual Employment OV-1

The weapons and sensors for individual TRUCCs are configurable by a land-based, forward-deployed support detachment. The operational TRUCC support staff determines weapon and sensor configuration based on intelligence analysis of enemy tactics and disposition in much the same way that loadouts are specified for strike aircraft in today's carrier airwing. The potential exists to field a TRUCC team with heterogeneous loadouts to account for different threats (for example, Anti-Ship Cruise Missile (ASCM) and FAC/FIAC within a single mission).

Due to limited size of the TRUCC, the mission duration is limited to brown- and green-water operations. Refueling at land-based maintenance depots affords opportunities for frequent maintenance operations resulting in increased mid-mission reliability. This operational employment concept represents a realistic and achievable method of integrating USVs into the future Navy's force structure and deployment methods in the littoral environment.

VI. TRUCC FORCE PROTECTION MODELING

A modeling effort was necessary to provide quantitative weight behind the major vessel characteristics that contribute significantly to mission success. The quantitative analysis evaluated the relative benefits of various areas in the vessel design trade space. Based on the operational employment concept, a single TRUCC vessel type will be able to confront a variety of threats. Modeling was necessary to determine what design factors were the most important. For example, as shown in Table 6, the most important design factors are weapon firing rate, number of TRUCCs and weapon Probability of kill (Pk). The numerous trade-offs associated with TRUCC vessel characteristics were examined through Model-Based Systems Engineering to verify the importance of the design factors.

For the modeling phase, the project team re-organized into three distinct modeling groups: Mission Effectiveness (ME), Mission Vehicle (MV) and Operational Availability (Ao). The division of labor allowed more efficient use of project team resources.

The Mission Effectiveness group was responsible for agent-based simulation of the tactical scenario. The Mission Effectiveness group used a program developed by the New Zealand military called Map Aware Non-Uniform Automata (MANA).[14] MANA provided the ability to model inter-squad intelligence reflective of groups of networked TRUCCs operating as a cohesive team to defeat an unpredictable incoming threat. The Mission Effectiveness group focused on ranges of vessel speeds, sensor ranges and weapon characteristics, rather than modeling simple point values. This modeling process allowed development of sensitivities that lead to identification of key performance characteristics.

[14] (McIntosh, Galligan, Anderson, & Lauren, 2007)

The Mission Vehicle group was responsible for conducting basic ship synthesis for vessels with the characteristics employed by the Mission Effectiveness group. The group applied regression techniques, parametric analysis, system research and stakeholder feedback to develop three general types of USV hulls. The ship synthesis also identified the associated weapons and sensors capabilities that these hulls could reasonably employ.

The Operational Availability group modeled the total number of TRUCCs required in theater based on operational availability and reliability data derived from the DRM. The purpose of this analysis was to determine the anticipated fleet requirements for the employment of this USV.

Each modeling group produced a detailed discussion on the technical aspects of their modeling efforts, which is included for further review in the Technical Compendium section of this report. The overarching concepts and limited results of each group are discussed in the next section.

A. MODELING GROUP INTERACTIONS

To derive a holistic picture of the TRUCC operational modeling, the modeling groups were highly interactive. The Mission Effectiveness group chose to model the TRUCCs using a wide-range of generic capabilities (e.g., speed, weight, weapon ranges, and firing rates). These generic capabilities were not tied to specific weapon systems, sensors, or platform types; however, current systems were used to form analogues for modeling. For each variable, an upper and lower bound were selected, and explored through a half-factorial design of experiments. For example, the modeled firing rate of a medium caliber weapon was a range that included the actual firing rate of a 25MM gun.

To ground the modeling assumptions in reality, the Mission Vehicle group translated the generic capabilities into the physical domain (e.g. converting vessel speed and weapon firing rate into hull size and weapon type). The ME group modeled a 30-knot vessel that carried a long-range sensor and 20 long-range missiles. The MV group translated the required mission equipment capability into payload, and conducted ship synthesis to generate a conceptual vessel capable of meeting the requirement. As previously discussed, the MV group anchored the ship synthesis to three distinct ranges of vessel sizes to scope the ship synthesis effort.

The Operational Availability took the vessel characteristics, extrapolated endurance and reliability factors, and matched them to the DRM requirements. The extrapolation generated the total required force structure to accomplish the given DRM, accounting for combat operations, maintenance downtime and mid-mission failures. These interactions are shown in Figure 13.

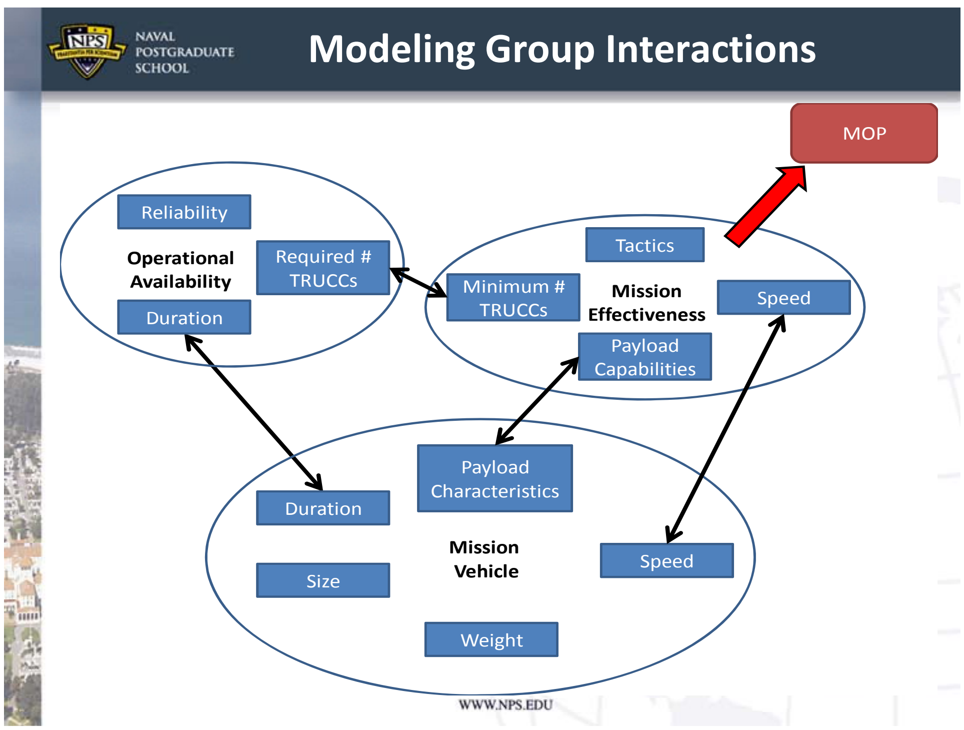

Figure 13. Modeling Group Interactions

It is important to note that this modeling triad was run in several different ways. Modeling teams, starting with an end-state Measure of Performance (MOP), generated the total required force structure in theater. Alternatively, the modeling teams started with a given number of TRUCCs and assessed the total combat capability of a TRUCC fleet, given a certain size and type of vessel.

While this front-end analysis functioned primarily to determine the total required force structure to support a single DRM, the modeling method and programming generated by this study could be easily adapted to assess combat capability in many different regimes. Additionally, only the Force Protection DRM was modeled by the ME group. Developing modeling for other DRMs would allow a similar analytical process and output, while leveraging modeling work already completed by this project team.

B. MISSION EFFECTIVENESS GROUP

The ME group determined the physical characteristics of the TRUCC that had the greatest impact on mission success and the effectiveness of TRUCC designs proposed by the MV group.

To execute this tasking, the group investigated several different modeling programs. Most modeling programs do not allow for effective modeling of the proposed cooperative engagement tactics and intelligence of a group of TRUCCs. An extensive search led to MANA. MANA is an agent-based model; meaning that the entities inside the model are controlled by individual decision-making algorithms. Once the simulation starts, the user takes no part in controlling the agents' actions.[15] Each agent develops its own situational awareness and evaluates appropriate actions using assigned sensors, weapons, and communication links. This program had the additional benefit of allowing users to watch a two-dimensional "battle" unfold between the threat systems and defending TRUCCs. Viewing these combat interactions in real time allowed for trouble-shooting of parameters and analysis of results that would not be possible with "black box" modeling software.

[15] (McIntosh, Galligan, Anderson, & Lauren, 2007, p. 5),

C. MULTI-THREAT FORCE PROTECTION DRM IN DETAIL

The initial Force Protection DRM was combined with the operational concept to develop a more thorough understanding of real-world employment to aid in modeling. In this scenario, the TRUCCs deployed to protect otherwise defenseless HVUs operating in the Straits of Hormuz. Given that not all sizes of TRUCCs were capable of effective open-ocean transit, they were delivered via maritime prepositioning assets to a Forward Operating Base (FOB) at Jebel Ali. The TRUCC fleet was supported by a forward-deployed maintenance, operational and force protection detachment. The TRUCCs protected the HVUs in both directions through the Straits of Hormuz by rendezvousing at marshaling areas in the Persian Gulf and Gulf of Oman. An overview of the area of operations is shown in Figure 14.

Figure 14. Persian Gulf and Gulf of Oman Area of Operations[16]

Upon rendezvous with the HVU, the TRUCC Force Protection patrol formed a defensive screening formation approximately 2000 meters in diameter.

[16] (ArcGis, 2012)

It is important to note that developing advanced tactics for convoy escort was beyond the scope of this report. A simple screening formation was chosen as a representative defensive tactic; however, further tactics development may reveal alternative formations or changes to the defensive radius that provide increased effectiveness.

1. Attacker Capabilities

The attackers for this DRM fall into three categories, and execute two different types of behaviors. The threat types are:

a. Fast Attack Craft / Fast Inshore Attack Craft

These are representative of small, fast and maneuverable boats commonly employed by threat nations in littoral waters. They can employ simple, short-range weapons, or act sacrificially, as in the bombing of the USS Cole (DDG 67).

b. Low Slow Fliers

Low slow flying air vehicle threats involve small planes, helicopters and unmanned aerial systems of all types. These systems are difficult to detect, carry heavy payloads and may employ tactics and maneuvers not achievable by missile systems.

c. Anti-Ship Cruise Missiles

Fast-moving missiles designed specifically for ship engagements pose a particularly difficult engagement problem for any defensive system.

D. ATTACKER BEHAVIOR

The LSF and the FAC/FIAC attackers can exhibit two distinct types of behavior: smart or dumb. Dumb attackers do not try to avoid the TRUCCs, even when detected. This behavior simulates attackers that drive towards the HVU regardless of defender tactics or capabilities. Smart attackers attempt to avoid the TRUCCs while still trying to reach the HVU. These different tactics represent two possible attacking system behaviors. There is a wide variety of tactics and geographic and temporal distributions available to swarm attackers. These two behaviors constrained the problem to a workable variable space; the time constraints of the project prevented the use of a greater number of threat systems combinations.

The characteristics of threat systems were derived from the performance of high-technology fielded systems of today. The underlying assumption was that the difficult-to-produce, high-technology fielded systems of today will be highly proliferated in the future. These threat systems will likely be used for swarm attacks over the 40–50 year time span of this study. This study made no attempt to conduct analysis on disruptive weapons technologies of the future. Those disruptive technologies will undoubtedly influence the battlespace; however, they are less likely to proliferate in the time scope of this project. Anticipating and planning defensive systems for possible future disruptive weapons technologies is beyond the scope of this study. The characteristics of each threat system are available in Table 5.

For the purposes of modeling, the threat swarms were assumed to be homogenous. Theoretically, threat swarms could be heterogeneous, utilizing combinations of threat systems to complicate the threat scenario. Initial modeling with homogenous threats revealed sensitivities against each type of threat, eventually allowing operational decisions regarding TRUCC weapon loadouts against heterogeneous threats.

Table 5. Threat Performance Characteristics

Red Enemy	ASCM	LSF	FAC/FIAC
Number of Red	60	60	60
Speed of Red (m/s)	1012	111	20.58
Sensor Detection Range (m)	15000	15000	15000
Sensor Detect Probability	1	1	1
Weapon Range (m)	200	200	200
Weapon P_K	1	1	1
Weapon Firing Rate (sec)	1	1	1

E. MEASURES OF EFFECTIVENESS AND PERFORMANCE

Based on the DRM, a causal diagram in Figure 15 shows the factors that impact mission effectiveness.

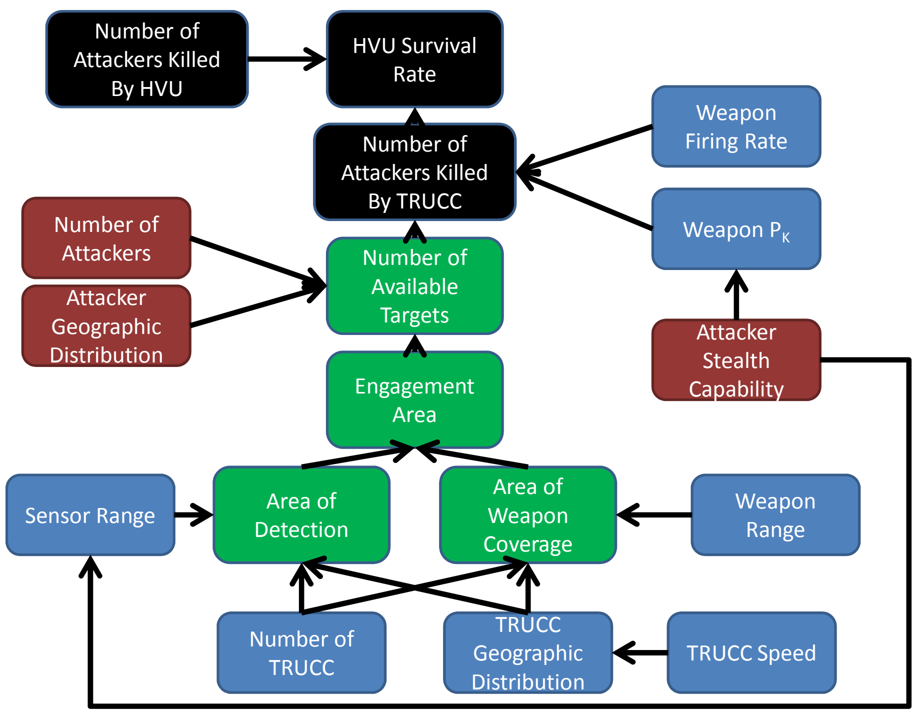

Figure 15. Mission Effectiveness Factors

The red and blue factors listed in the diagram are the independent characteristics of the TRUCC and the attackers in the DRM. All of these factors combine to determine the values of the secondary factors in green. These factors combined with additional independent factors to determine the tertiary factors (shown in black) where the Measures of Effectiveness (MOE) for the system are determined.

The MOE for the DRM in question was the probability of survival of the HVU. The primary supporting MOPs were the number of attackers killed by the HVU and TRUCCs, respectively. The threat system's effective Probability of kil was 1; if it evaded the HVU or TRUCC defenses, the HVU would suffer a mission kill. Each HVU had its own defensive capabilities, ranging from robust layered defensive systems (such as DDGs) to no defensive equipment (such as Military Sealift Command vessels).

The wide range of defensive capabilities made it impractical to derive DRM MOE directly. Therefore, the number of attackers killed by the TRUCC fleet was the modeling analysis tool for this DRM. By assuming a defenseless HVU, the analysis focused on TRUCC parameters, and avoided interdependencies caused by interactions with HVU targeting systems. Operational-level tactical considerations of cooperative engagement between manned and unmanned systems exist for further development. As such, the primary analysis metric for Mission Effectiveness was the MOP "number of attackers killed by TRUCCs."

1. Modeling Analysis

The ME group conducted a half-factorial design, selecting 64 scenarios coupled with 10 additional center-point scenarios, for a total of 74 modeling runs. Each scenario was repeated eleven times for a total of 814 runs. This design identified primary factors of importance, as well as second-order interactions. The factor summary is shown in Table 6. Factor 1 is the most significant; Factor 5 is the least. Each factor is color-coded for ease of identification of like factors.

Table 6. Mission Effectiveness Dominant Factors

Scenario	Missile Dumb	UAV Dumb	UAV Smart	USV Dumb	USV Smart
Factor 1	Weapon Firing Rate	Weapon Firing Rate	Weapon Firing Rate	Number of TRUCCs	Sensor Range * Weapon Range
Factor 2	Weapon Pk	Number of TRUCCs	Weapon Pk	Sensor Range * Weapon Range	Weapon Range
Factor 3	Number of TRUCCs	Weapon Pk	Number of TRUCCs	Weapon Range	Number of TRUCCs
Factor 4	Sensor Range	Sensor Range	Weapon Pk * Weapon Firing Rate	Weapon Pk	Weapon Pk
Factor 5	Weapon Pk * Weapon Firing Rate	Sensor Range * Weapon Range	Number of TRUCCs * Weapon Firing Rate	Weapon Firing Rate	Weapon Firing Rate

Table 6 shows that the dominant factors are:

- Number of TRUCCs (force ratio)
- Weapon Probability of kill
- Weapon firing rate

With the primary sensitivities generated, a stepwise regression process was used to form a model that predicted the number of threat systems killed, given TRUCC capabilities. The Mission Vehicle group provided the characteristics shown in Table 7 for the respective types of TRUCC hulls.

Table 7. TRUCC Design Specifications[17]

TRUCC Design Specifications	Small	Medium	Large
Speed of TRUCC (m/s)	20.58	20.58	20.58
Sensor Detection Range (m)	16400	22700	55300
Sensor Detect Probability	0.5	0.5	0.5
Number of Missile Launchers	0	0	1
Missile Range (m)	20000	20000	20000
Missile Pk	0.7	0.7	0.7
Missile Firing Rate (cycle time sec)	1	1	2
Number of Medium Caliber Machine Guns	0	1	3
Medium Caliber Machine Gun Range (m)	2700	2700	2700
Medium Caliber Machine Gun Pk (per round)	0.0001	0.0001	0.0001
Medium Caliber Machine Gun Firing Rate (rounds/minute)	300	300	300
Number of Small Caliber Machine Guns	3	5	3
Small Caliber Machine Gun Range (m)	2000	2000	2000
Small Caliber Machine Gun Pk (per round)	0.0001	0.0001	0.0001
Small Caliber Machine Gun Firing Rate (rounds/minute)	550	550	550

Table 8 shows the number of TRUCCs required to destroy the entire threat swarm in 100 out of 100 trials.

Table 8. Required Numbers for 100% Red Casualties

Required Numbers for 100% Red Casualties			
THREAT	SMALL	MEDIUM	LARGE
DUMB ASCM	32	14	3
SMART LSF	13	12	3
DUMB LSF	15	7	3
SMART FAC/FIAC	6	3	3
DUMB FAC/FIAC	6	3	3

The results from the design evaluation supported the factor exploration results. The Large TRUCC, which had the longest weapon range and highest Probability of kill, was the most effective against both the missile and LSF threats. The Small and Medium TRUCCs performed almost equally against the

[17] (Tibbitts, 1998, p. 5)

Smart LSF threats; however, there was a major difference between the number of Medium TRUCCs and Small TRUCCs needed to counter the Dumb LSF threat.

In this scenario, the medium-caliber weapon of the Medium TRUCC was able to engage enough incoming Dumb LSFs that they did not overwhelm point defenses. Interestingly, Small TRUCCs were overwhelmed by the Dumb LSF threat. The near-simultaneous arrival of Dumb LSFs, coupled with the Small TRUCC's short range, small-caliber weapons combined to generate a more stressing scenario than the Smart LSF threat. Smart LSFs circled around the Small TRUCC defensive formation, and attacked the HVU in small groups, or as singles, when opportunities presented themselves.

F. TIME DELAY MODELING

Additional modeling was conducted to explore the effects of time delay in the identification of the attacker. This modeling effort was designed to simulate a man-in-the-loop scenario by generating a situation in which an attacker was detected, but positive hostile identification was delayed, potentially due to the need for interaction with a manned control station prior to weapons release authorization. In previous modeling, TRUCCs could engage attackers upon initial detection because classification occurred at the same time as detection (assuming the unmanned system had the authority to classify an inbound track as hostile and engage with lethal force). This assumption represented the least stressing case, because there was no time delay associated with the need for human decision or communication latency. To gain a better understanding of the effects of that assumption, the team developed a new scenario to examine delays in the detect-to-engage sequence of up to ten seconds.

1. Time Delay: ASCM Impact

For ASCM engagements, because the relative rate of closure was extremely fast, sensor range became increasingly important as the classification delay increased. Absent a delay, the TRUCCs were able to react immediately to the hostile threat; therefore, more defensive weapons were applied towards the threat, improving the overall probability of survival. As classification delay increased, fewer defensive engagements were possible and the probability of survival decreased significantly. As anticipated, there was a significant tradeoff between sensor range and the human or machine agent's ability to classify a threat which can only be mitigated through the employment of long-range sensors and/or faster classification and engagement.

2. Time Delay: LSF Impact

For both Smart and Dumb LSF engagements, time delays up to ten seconds had no effect on the factors of importance. Since LSFs were much slower than the missile threat, sensor range was not a significant factor. With longer-delay durations (not evaluated here based on the front-end assumption that ten seconds was the maximum relevant delay) sensor range became important, as seen in the ASCM instance.

3. Time Delay: FAC/FIAC Impact

For Dumb FAC/FIAC scenarios, as delay increased, sensor range became more important because the number of TRUCCs became less important. The FAC/FIAC was the slowest moving of the threats. Against slow-moving threats, TRUCCs had sufficient time to maximize the use of their defending forces, even if equipped only with short-range weapons. As the time delay increased, the importance of early warning from a long-range sensor increased.

In the smart FAC/FIAC scenario, as with the dumb FAC/FIAC scenario, sensor range became more important with increasing time delays. In this instance, though, weapon range remained the most important factor as the delay increased. This was due to the maneuvers performed by the smart FAC/FIACs attempting to find a gap in the defenders.

4. Scalability

Modeling was conducted to examine the effects of scalability upon system performance. Holding the force ratio between the TRUCCs and the attackers constant, the total number of attackers was multiplied by two, three, and five. The red attack force was fully destroyed in every scenario regardless of the multiplier used. From these results it is safe to conclude that the TRUCC system performance is close to linear (red force attrition proportional to blue force level) if the force ratio is held constant.

G. MISSION VEHICLE GROUP

The Mission Vehicle group used an engineering perspective to calculate objective attributes for a given set of design variable values. The goal of the model was to use fixed mission parameters such as speed, total displacement, and type of hull to return capabilities and figures useful to other groups for further analysis. Detailed naval architecture is beyond the scope of this Systems Engineering study, and remains for follow-on study. The efforts of the MV group are, however, rooted in naval architecture principles through the use of ship synthesis methods. Ship synthesis is a technique to allow early stage vessel development with the limited data available.[18] Ship synthesis calculations are rooted in naval architecture principles without requiring detailed ship specifications.

During initial scoping, the MV group limited hull types to monohull designs due to the vast number of ships in existence using this hull form, its low technological risk, suitability in the littoral environment, and necessity for potential low-speed operations derived from early screening experiments. Additionally, only maritime diesel propulsion was examined; it is a mature and reliable technology currently employed in vessels conducting the operations proposed in the operational concept. This assumption was corroborated by the reliability

[18] (Choi, 2009, p. 12)

dependencies on mission effectiveness by the Operational Availability group detailed later in the report. Based on these initial assumptions, the TRUCC vessels fall into three distinct size categories; small, medium, and large. The general characteristics are summarized below and discussed further in the Mission Vehicle Technical Compendium.

1. Small TRUCCs

i. Length to Beam Ratio (L/B) is approximately equal to 3:1

ii. Beam to Draft (B/T) ratio is approximately equal to 2:1

iii. Length ranges from 6 to 36 feet

iv. Small-caliber weapons

2. Medium TRUCCs

i. L/B is approximately equal to 4.1:1

ii. B/T is approximately equal to 3.1:1

iii. Length ranges from 37 to 90 feet

iv. Small-caliber weapons

v. Medium-caliber weapon

3. Large TRUCCs

i. L/B is approximately equal to 5.25:1

ii. B/T is approximately equal to 3.125:1

iii. Length ranges from 90 to 200 feet

iv. Small-caliber weapons

v. Medium-caliber weapon

vi. Directional missile launcher

H. WEAPONS

Each size of TRUCC was capable of employing specific weapon systems based on available payload. The weapons available aboard each size of TRUCC were based on the arming scheme currently employed for corresponding manned combat vessels. The TRUCCs have the characteristics featured in Figure 16.

	Small Caliber	Medium Caliber	Missile
Small	x		
Medium	x	x	
Large	x	x	x

Figure 16. Available Weapons by TRUCC Size

It is critical to note that the unmanned vessel arming employment may shift in the future. For example, technological advancements may allow directional missile launchers to be placed on Small or Medium TRUCCs because there is no missile backblast risk to crewmembers. This analysis limits the arming employment to those demonstrated on manned vessels. This is a somewhat conservative assumption. It prevents the group from making convenient assumptions without the requisite naval architecture and weapon system analysis. Because unmanned systems do not require habitability systems, later-stage detail design may result in increased combat system capability or weapon system load-out on smaller vessels.

Specific weapon systems were not evaluated in the study; rather, a range of weapon capabilities were considered. The three types of weapons investigated were:

- Small caliber weapons: Low mass projectiles, low single-shot probability of kill (Pssk), very high rate of fire

- Medium caliber weapons: Medium mass projectiles, medium Pssk, high rate of fire
- Missiles: Guided, fused projectiles, high Pssk, medium rate of fire

1. Small Caliber

Examining multiple manned combat vessels revealed a relationship between vessel length and the number of small caliber weapons. For every 12.7 feet of length, there can only be one small caliber weapon. The representative weapons system for small caliber munitions was the GAU-19 machine gun.

2. Medium Caliber

Using the manned systems scheme, a single medium caliber weapon was placed on all medium class ships and above. A representative weapon system for this class of weapon is the 25mm MK38 Mod 2 machine gun.

3. Missiles

A directional launch missile system was placed on Large TRUCC variants. A Vertical Launch System (VLS) was not considered due to space and weight constraints on vessels of this size. The weights of the systems included launcher, fire control (guidance) and missile magazine. Representative weapon systems for this class of weapon are the RIM-162 Sea Sparrow and the RIM-116.

I. VESSEL CHARACTERISTICS AND PERFORMANCE

By examining the characteristics of existing combat vessels, the MV team created a series of regressions to generate TRUCC characteristics and performance data estimates. For example, a series of existing combat vessels ranging in length from 7’ to approximately 200’ were examined. Using standard naval architecture characteristics, such as block coefficient (C_b) and L/B, the MV group started with ship displacement and worked backward to produce predictions of vessel length. Notably, this research noted inflection points at both

150 long tons (LT) and 70 LT, necessitating a series of nested If/Then statements in the spreadsheet model to ensure accurate estimation throughout the given TRUCC length range. The resulting calculations were then validated by taking known combat craft displacements and estimating length, as shown in Figure 17.

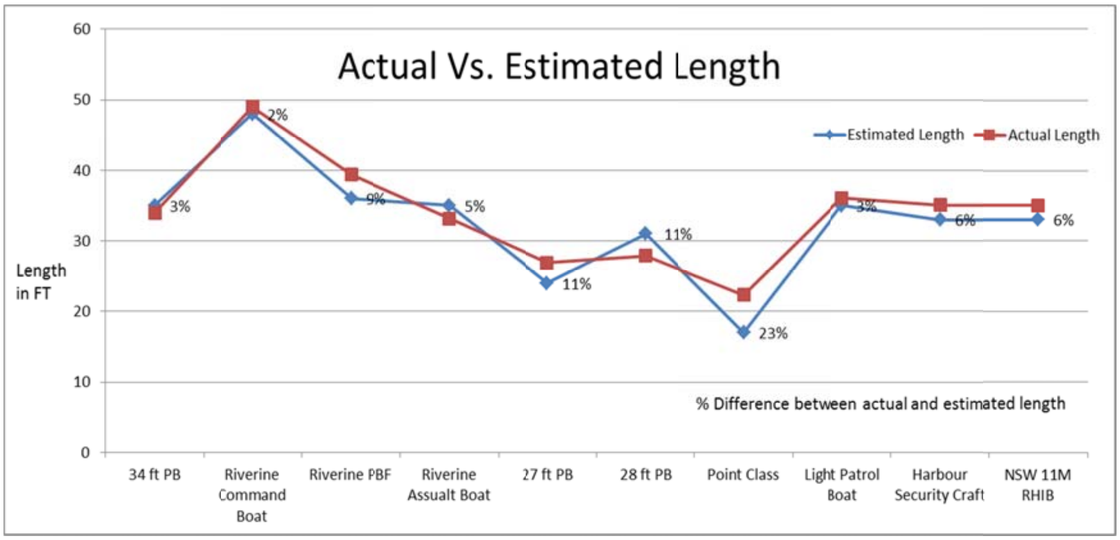

Figure 17. Actual vs. Estimated Length of TRUCC

Several other regressions were conducted; these are located in the Mission Vehicle Technical Compendium. The regressions performed are length on:

- Horsepower / speed
- Fuel weight / capacity
- Endurance

J. SENSORS

Another key area of focus was the sensor performance. The sensor range required to satisfy the littoral DRMs was less than 25 nautical miles. Sensor systems with lower detection and classification ranges are typically smaller and of lower weight.[19] Therefore, sensor weight was not a significant factor when determining overall payload capacity for the USV. Initially, an attempt was made to place representative radar systems onboard the TRUCC keeping weight requirements in mind. Since most radars take up a fraction of the total displacement while still being able to see over the horizon, the model derived sensor performance from the simple radar range equation. It will be up to detailed design to determine specific requirements for a sensor system that meets the specified performance criteria required for the size of the USV.

K. TRUCC CHARACTERISTICS

Representative Mission Vehicle model outputs are shown for each TRUCC size in Tables 9 through 11. These simple Microsoft Excel® models used five inputs to generate several outputs of which six were paramount to design configuration. The inputs (highlighted in yellow) are the requirements for mine hunting, the desired speed, total USV displacement, and height of the target. Based on these inputs the model provided the team with required USV dimensions, horsepower, endurance at maximum and cruise speeds, and weapons systems capacity and key performance characteristics.

Figure 18. Small TRUCC Rendering

[19] (Harney, Radar Weight Requirements , 2012)

Table 9. Small TRUCC Characteristics

Hull Type		Monohull	1	***Output***	***MONOHULL***		
1		Catamaran	2	**Weapons**			
Mine Hunting Required ?	**Yes or No**	Triamaran	3	*Payload*	**Missile**	**not capable**	**0**
yes		M Hull	4		Maximum Effective Range	n/a	yds
					Probability of Kill	n/a	
User Inputs					Fire Rate	n/a	sec btwn shots
Speed		40	kts		**Medium Caliber Weapon**	**Amount**	**0**
Payload - Sensor			Long Tons		Maximum Effective Range	2700	yds
Payload - Weapon			Long Tons		Pk 1000	0.8	
Sea State					Pk 500	0.83	
Total Displacement		4	Long Tons		Pk 100	0.887	
Height of Target		200	ft		Fire Rate	180	rds/min
					Small Caliber Weapon	**Amount**	**3**
USV Specifications					Maximum Effective Range	1900	yds
Length		27	ft		Pk 1000	0.68	
Beam		9	ft		Pk 500	0.7	
Draft		4	ft		Pk 100	0.745	
Height		18	ft	*Payload*	Fire Rate	1300	rds/min
Horsepower		363	HP	**Sensor**			
Range at Max Speed		106	nm	*Payload*	Range of Detection	45200	yds
Range at Cruise Speed		152	nm	*Payload*	Probability of Detection	0.9	
Organic Asset	**Unsupported**	RMMV			Mine Range of Detection	n/a	yds
Length		23	ft		Probability of Detection	0.9	
Diameter		4	ft	**Performance**			
Vessel Definition		(+/-) 20 %		*Speed*	Cruise Speed	28	kts
Small		6-36 feet		*Speed*	Max Speed	40	kts
Medium		37- 90 feet		*Range*	Endurance	3.8	hrs
Large		90-200 feet			Refuel Time	47	mins

Figure 19. Medium TRUCC Rendering

Table 10. Medium TRUCC Characteristics

Hull Type		Monohull	1	***Output***	***MONOHULL***		
1		Catamaran	2	**Weapons**			
Mine Hunting Required ?	**Yes or No**	Triamaran	3	*Payload*	**Missile**	**not capable**	**0**
yes		M Hull	4		Maximum Effective Range	n/a	yds
					Probability of Kill	n/a	
User Inputs					Fire Rate	n/a	sec btwn shots
Speed		40	kts		**Medium Caliber Weapon**	**Amount**	**1**
Payload - Sensor			Long Tons		Maximum Effective Range	2700	yds
Payload - Weapon			Long Tons		Pk 1000	0.8	
Sea State					Pk 500	0.83	
Total Displacement		68	Long Tons		Pk 100	0.887	
Height of Target		200	ft		Fire Rate	180	rds/min
					Small Caliber Weapon	**Amount**	**6**
USV Specifications					Maximum Effective Range	1900	yds
Length		69	ft		Pk 1000	0.68	
Beam		23	ft		Pk 500	0.7	
Draft		11	ft		Pk 100	0.745	
Height		46	ft	*Payload*	Fire Rate	1300	rds/min
Horsepower		1398	HP	**Sensor**			
Range at Max Speed		2794	nm	*Payload*	Range of Detection	51500	yds
Range at Cruise Speed		3992	nm	*Payload*	Probability of Detection	0.9	
Organic Asset	**Unsupported**	RMMV			Mine Range of Detection	n/a	yds
Length		23	ft		Probability of Detection	0.9	
Diameter		4	ft	**Performance**			
Vessel Definition		(+/-) 20 %		*Speed*	Cruise Speed	28	kts
Small		6-36 feet		*Speed*	Max Speed	40	kts
Medium		37- 90 feet		*Range*	Endurance	99.8	hrs
Large		90-200 feet			Refuel Time	46	**mins**

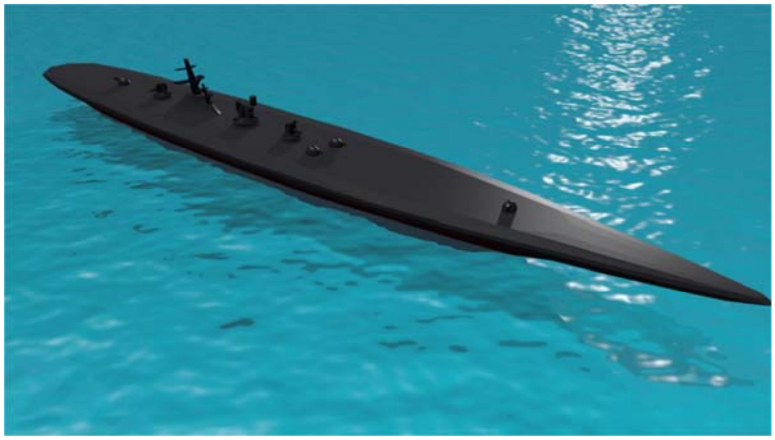

Figure 20. Large TRUCC Rendering

Table 11. Large TRUCC Characteristics

Hull Type		Monohull	1	***Output***	***MONOHULL***		
1		Catamaran	2	**Weapons**			
Mine Hunting Required ?	**Yes or No**	Triamaran	3	*Payload*	**Missile**	**missile capable**	**1**
yes		M Hull	4		Maximum Effective Range	20000	yds
					Probability of Kill	0.7	
User Inputs					Fire Rate	5	sec btwn shots
Speed		40	kts		**Medium Caliber Weapon**	**Amount**	**2**
Payload - Sensor			Long Tons		Maximum Effective Range	2700	yds
Payload - Weapon			Long Tons		Pk 1000	0.8	
Sea State					Pk 500	0.83	
Total Displacement		340	Long Tons		Pk 100	0.887	
Height of Target		200	ft		Fire Rate	180	rds/min
					Small Caliber Weapon	**Amount**	**15**
USV Specifications					Maximum Effective Range	1900	yds
Length		182	ft		Pk 1000	0.68	
Beam		35	ft		Pk 500	0.7	
Draft		11	ft		Pk 100	0.745	
Height		69	ft	*Payload*	Fire Rate	1300	rds/min
Horsepower		14620	HP	**Sensor**			
Range at Max Speed		2467	nm	*Payload*	Range of Detection	55300	yds
Range at Cruise Speed		3524	nm	*Payload*	Probability of Detection	0.9	
Organic Asset	**Supportable**	RMMV			Mine Range of Detection	Rng of Day	yds
Length		23	ft		Probability of Detection	0.9	
Diameter		4	ft	**Performance**			
Vessel Definition		(+/-) 20 %		*Speed*	Cruise Speed	28	kts
Small		6-36 feet		*Speed*	Max Speed	40	kts
Medium		37- 90 feet		*Range*	Endurance	88.1	hrs
Large		90-200 feet			Refuel Time	46	mins

It is important to note that these tables represent specific point values for TRUCC sizes within a range of available sizes for each group. Furthermore, the ship synthesis method will be further refined as detailed naval architecture and systems decisions are made regarding TRUCC design, and as such, these illustrative values should not be considered final design specifications. This ship synthesis process produced vessel performance and characteristic data sufficient for further use by the Operational Availability and Mission Effectiveness groups.

L. OPERATIONAL AVAILABILITY GROUP

Any discussion of USVs is incomplete without a discussion of Operational Availability (Ao). The operational concept provides opportunities for TRUCCs to receive maintenance at a forward operating base. Though forward-deployed maintenance facility is certainly a force-multiplier, it is critical to model the maintenance downtime implications on the TRUCC fleet operational capability. Furthermore, even well-maintained TRUCCs will suffer mid-mission failures at some point. Both of these immutable facts of military operations generate the need for more TRUCCs beyond the minimum number required for threat mitigation.

The operational availability modeling was conducted using ExtendSim® 8.0 stochastic modeling software. The software provided an easy-to-use interface allowing the group to connect simple functional blocks to mimic complex real-life processes. A representative model is shown in Figure 21. The complete model is discussed in detail in the Operational Availability Technical Compendium.

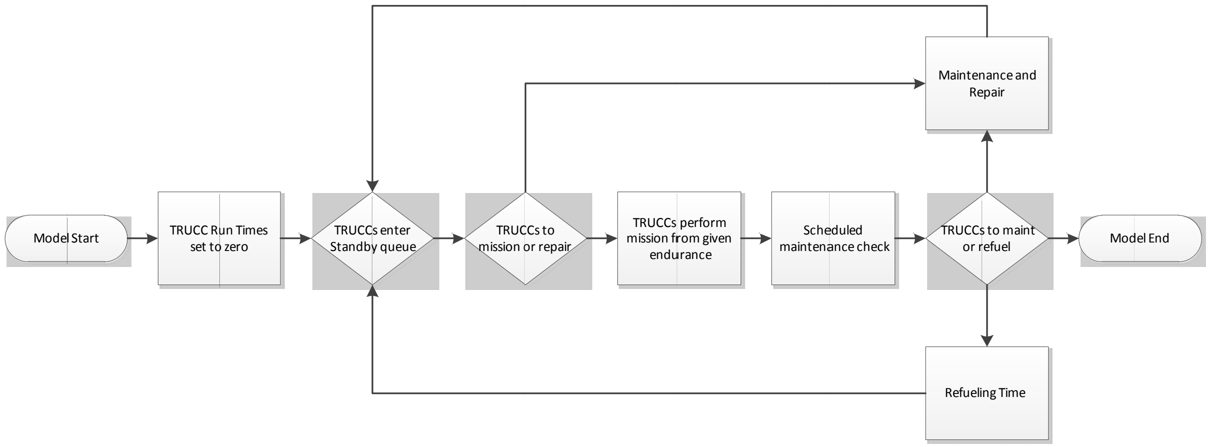

Figure 21. Ao Representative Model Screenshot

The ExtendSim® modeling accounted for the additional force structure required to account for both maintenance and mid-mission failures as shown in Figure 22.

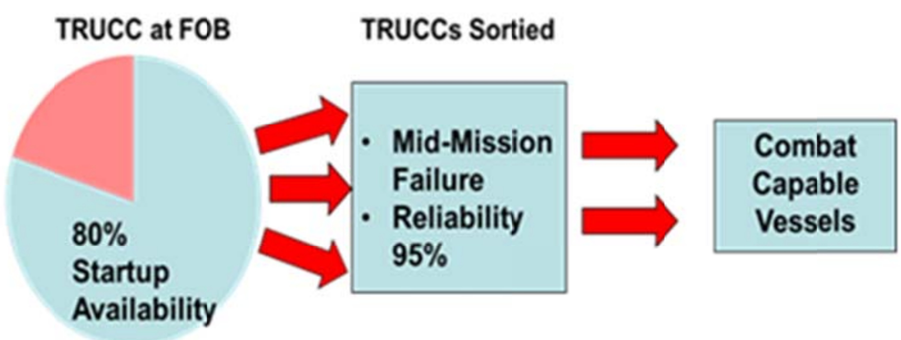

Figure 22. TRUCC Ao Description

M. DESIGN OF EXPERIMENTS

Using JMP®, a design of experiments (DOE) was conducted on the model input factors of endurance, refueling, and maintenance. JMP® is a statistical analysis program that provides several tools for assessing a large amount of data to identify relevant information and conclusions.[20] The DOE created by JMP® was a randomized experiment using three factors, each with nine levels, resulting in a 9x9x9 full factorial design randomized screening experiment, totaling 729 total runs, to determine which, if any, of the factors were significant. The other input variables (reliability, number of hours for the model, number of TRUCCs that can be on mission, the number of TRUCCs that can be repaired or maintained at the same time, and the number of hours before routine maintenance) were held constant within the model. The screening experiment used an assumed 0.8 start-up operational availability factor, 5,000 hours for the run time, 30 TRUCCs required on mission, five TRUCCs repaired at a time, and 1,500 hours for routine maintenance.[21] Table 12 covers the stochastic variables and associated distributions utilized for this analysis.

Table 12. Statistical Distribution Table

Statistical Distribution Table			
Factor	**Distribution Type**	**Mean**	**Standard Deviation**
Endurance	Normal	Varied between TRUCC Variants	30 minutes
Refueling	Normal	45 minutes	6 minutes
Maintenance	Poisson	Varied between TRUCC Variants	--

N. MODELING INPUTS

The number of vessels in the “TRUCC Pool” accounted for maintenance downtime; at any given time, it assumed that only 80% of TRUCCs would be operationally available for sortie. Put another way, 80% of TRUCCs exhibit “start-up availability”; they would be ready to commence a mission at any given random time. Startup availability was a deterministic point value derived from

[20] (SAS Institute Inc, 2012)

[21] (Caterpillar Corporation, 2011, p. 2)

extrapolation of currently fielded maritime combat systems and from operational experience.[22] Accounting for the maintenance downtime helped determine the total number of TRUCCs required for mission success.

Poisson distributions were not used because true independence cannot be assumed in a managed maintenance pool since vessels are often cannibalized for parts to maximize operational availability of the group and maintenance procedures are planned around scheduled operations. These procedures are similar to accepted aviation squadron maintenance procedures. Currently fielded combat systems exhibit operational availability as shown in Table 13.

Table 13. Operational Availability of Currently Fielded Systems[23]

Platform	Operational Availability
Coastal Patrol Craft (PC)	0.62
Ohio Class Nuclear Powered Submarine (SSBN)	0.68
Forward deployed Guided Missile Destroyers (DDG)	0.2
Los Angeles Class Nuclear Powered Submarine (SSN)	0.6

Given the proposed concept of operations, the assigned start-up availability of 0.8 was a reasonable assumption based on the values of currently fielded systems represented in Table 13 and Table 36. TRUCCs are smaller and less complex than the given systems. Furthermore, the littoral environments will limit long patrols, creating more opportunity for preventative maintenance to

[22] (Congressional Budget Office, 2007, p. 20)

[23] (Congressional Budget Office, 2007, p. 20)

ensure high levels of availability. It is important to stress that this value was a starting value for analysis. Explicit availability values should be based on further specification of the scenario and system parameters.

Maintenance requirements were modeled using analogous maintenance requirements for diesel propulsion systems. Diesels are currently fielded on manned vessels within the size ranges specified by the Mission Vehicle group. Furthermore, these propulsion systems exhibit relatively high levels of reliability, i.e., they are mature technologies. Other technologies may be worth investigating; however, Table 6 shows that the speed of the TRUCCs was not a major factor in to achieve the measure of performance; there is no need for cutting-edge propulsion technology. As such, analysis was limited to maritime diesels.

The mid-mission reliability of individual TRUCCs was assumed to be 95%. Achieving this high level of reliability is critical to unmanned system performance. Without a man-in-the-loop for mid-mission repairs, potential failures pose a significant vulnerability and liability for the operation. USVs that fail mid-mission are susceptible to exploitation by enemy actors, pose hazards to navigation, may injure innocents, and/or may require extensive employment of assets for vessel recovery operations. For these reasons, it was reasonable to look for reliability paradigms from other communities where mid-mission reliability is mission critical, such as the aviation community. For example, the Extended Range Multi-Purpose (ER/MP) UAS regularly achieves an overall system operational availability greater than 0.9.[24] Using the aforementioned example, the TRUCC system was assumed to achieve a reliability of no less than 0.95 to deploy, complete the mission, and return to base.

Throughout the analysis, maintenance times were scaled based on TRUCC size category. Small TRUCCs were assumed to require maintenance

[24] (General Atomics Aeronautical Systems, 2010)

times 10% of the Large TRUCCs; Medium TRUCC maintenance required 67% of the Large TRUCC values. This graduated scale accounts for the complexity of conducting maintenance on larger vessels. For example, changing oil on a 7-meter RHIB is much less time-consuming than changing lube oil on a 200' coastal patrol craft. The percent difference between required maintenance times were based solely upon collective knowledge of the project team. Further analysis is required to identify the actual maintenance times.

O. MODEL ANALYSIS

The model output the number of TRUCCs required in inventory to achieve a given fielded combat capability. An example of this output is shown in Table 14 for Large TRUCCs defending against ASCM. This example table shows the number of Large TRUCCs required at a forward operating base to support a combat requirement of three vessels as average maintenance time increases.

Table 14. Large TRUCCs against ASCM

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
4	88.1	12	88.1	17.5	88.1	10
5	88.1	23.7	88.1	40	88.1	10
6	88.1	25	88.1	40	88.1	10

As depicted, the minimum number of TRUCCs required in inventory to achieve an average of three TRUCCs on mission was four. To maintain consistency with the baseline model, Table 14 only considers the TRUCC variants that meet the required minimum TRUCC count and depicts the total number required in inventory, the average maintenance times required supporting them, and the minimum and maximum value combinations required to meet mission requirements.

Maintenance times averaged 25 hours or less and averaged 12 hours for the worst-case scenario of only one spare TRUCC in inventory. Minimally increasing the number of TRUCCs in inventory by two drastically increased the allowable mean maintenance time from 17.5 to 40 hours.

With five TRUCCs in inventory, the average endurance was 88.1 hours with an average maintenance time of 23.7 hours. The maximum and minimum combinations of endurance and maintenance time were 88.1 hours of endurance with 40 hours of maintenance and 88.1 hours of endurance with 10 hours of maintenance respectively. Again, the number of TRUCCs in inventory affected how much maintenance time could be afforded to the TRUCCs and vice versa. As detail requirements are defined further cost study should be developed to examine the trade space between operational availability and the cost of high availability. Extra TRUCCs available in theater generate lower required maintenance and reliability specifications.

Similar data is available in the Mission Effectiveness Technical Compendium for all combinations of TRUCCs and DRM threat system/behavior combinations.

The impact of start-up availability is shown in Figure 23 comparing the Ao curves with the number of required TRUCCs in inventory. The number of TRUCCs required in inventory rapidly increases as Ao decreases.

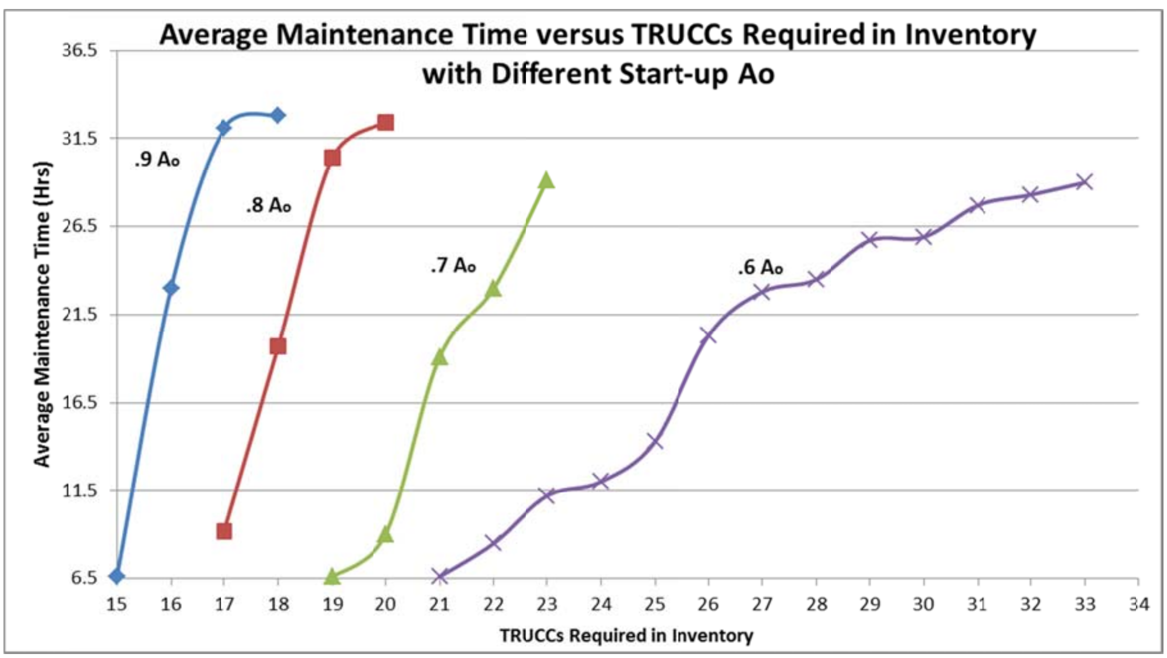

Figure 23. Average Maintenance Time versus TRUCC Required in Inventory for Different Operational Availabilities

Additionally, the impact of mid-mission failures was generated using the previously-discussed 0.95 reliability value. Using the same TRUCC and threat pairing, Figure 24 shows the impact of sending additional TRUCCs on a mission.

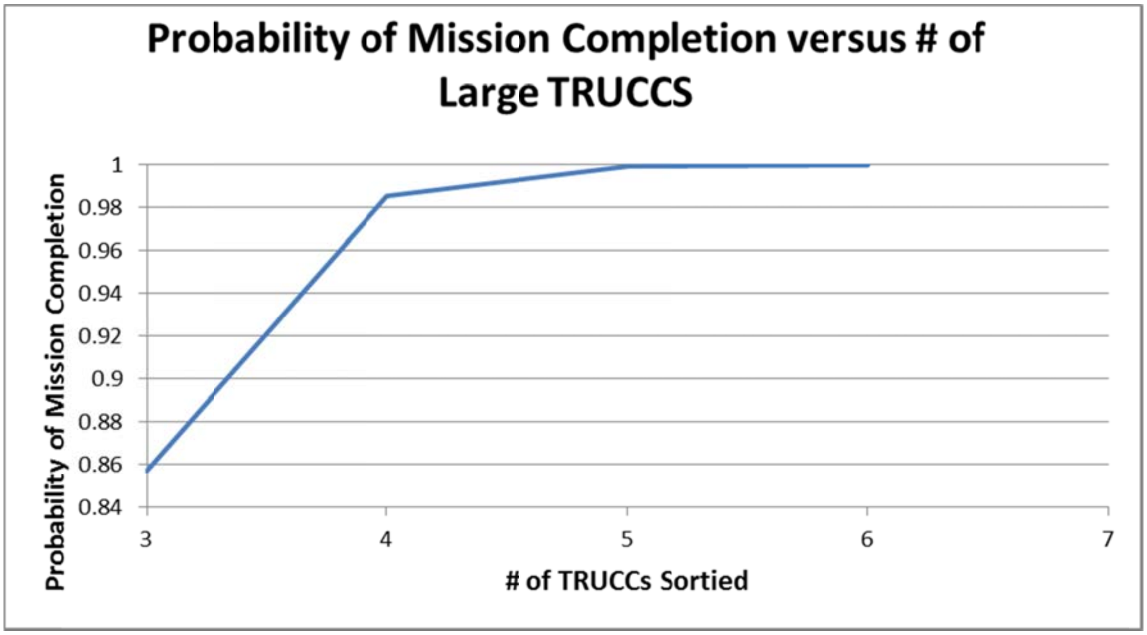

Figure 24. Probability of Mission Completion versus # of Large TRUCCs

If three large TRUCCs are required, and three are sortied, there is only an 86% probability of having at least three systems for the duration of the mission. If four TRUCCs are sortied, then mission there is a 99% probability of having at least three TRUCCs available for the entire mission duration. The calculations for small, medium and large are shown in section G of the Operational Availability Technical Compendium.

The analysis of Medium TRUCC reliability has more data points, which illustrates the diminishing returns of increased TRUCCs sortied on mission success, as shown in Figure 25.

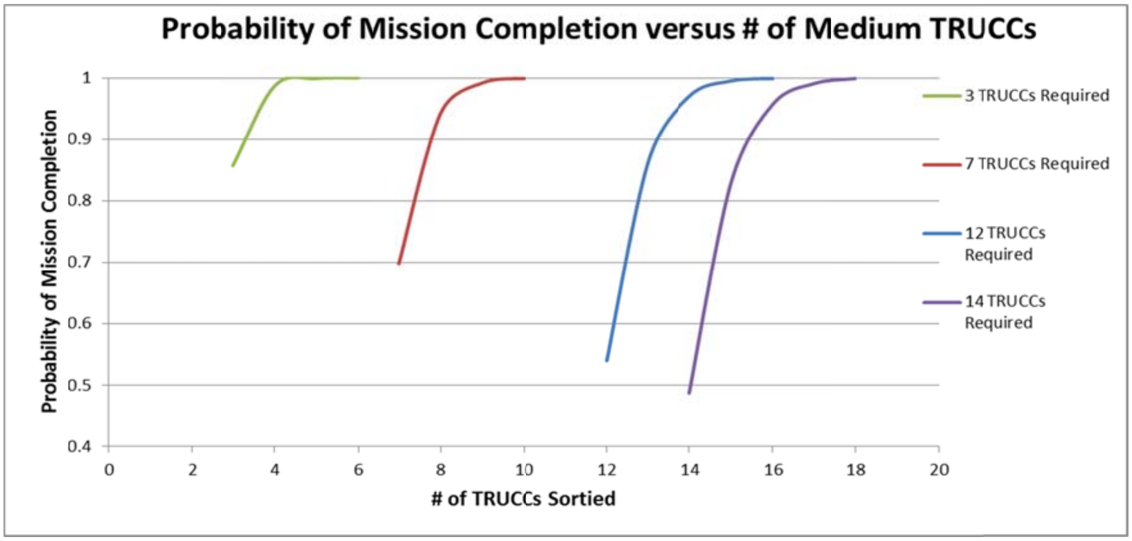

Figure 25. Probability of Mission Completion versus # of Medium TRUCCs

Probability of mission completion is defined as the chance that the total number of vessels required for combat operations are available throughout the given mission. Adding spare TRUCCs increases the overall probability of mission success. The impact of additional TRUCCs on probability of mission completion is greater as the required number of TRUCCs increases.

The complete data for this analysis is available in the associated Technical Compendium.

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VII. DOCUMENTING COST

Given that this is an early stage study, cost estimation was given some consideration; however, a complete cost estimation effort is left to follow-on study. Without a clear study of the manpower and cost necessary to develop autonomy, a complete cost estimation is not possible. Manpower to support unmanned systems is a study unto itself, and beyond the scope of this project, but represents an excellent area for further research.

It was possible, however, to generate initial order cost estimates for the USV major components. Procurement cost data for this project was derived using the analogy approach. Researching the total Other Procurement Navy (OPN) costs of the following platforms yielded a cost per linear foot for each platform. All figures were converted to FY12 dollars and are depicted in Table 15.

- DDG-51 Arleigh Burke Class Guided Missile Destroyer
- CG-47 Ticonderoga Class Guided Missile Cruiser (CG)
- Cyclone Class Coastal Patrol Class (PC)
- Mark V Special Operation Craft (MK V)
- 11 meter RHIB

Table 15. Cost Comparison of DDG-51, CG-47, PC, and TRUCC Variants

	Procurement Costs ($FY12M)	Weapon Systems ($FY12M)	Total Cost		Length (ft)	Cost p/ft ($FY12M)		Units p/ DDG	Units p/ CG
DDG	1836		1836		509	3.61		1	2
CG	3163.3		3163.3		567	5.58		1	1
PC	25.7		25.7		179	0.14		25	39
MK V	4.6		4.6		82	0.06		64	100
RHIB	0.85		0.85		33	0.03		140	217
Large TRUCC	25.7	2.2	27.9		179	0.16		23	36
Medium TRUCC	4.6	0.5	5.1		82	0.06		58	90
Small TRUCC	0.9		0.9		34	0.03		136	211

A. ASSUMPTIONS

The baseline cost of a Large TRUCC was assumed to be comparable to a new PC construction. In this instance, the PC's habitability systems are replaced with the autonomy systems required for unmanned operation. As depicted in Table 15, the cost of associated Large TRUCC weapon systems (if applicable) were in addition to baseline procurement costs and reflected in total costs.

The baseline cost of a Medium TRUCC was comparable to that of a new MK V. As depicted in Table 15 the cost of associated TRUCC weapon systems (if applicable) were in addition to baseline procurement costs and reflected in total costs.

The baseline cost of a Small TRUCC is comparable to that of an 11-meter RHIB. Small-caliber weapon costs were negligible and not included in overall cost of procurement

Using this data and the number of TRUCCs required for each threat scenario, a cost plot was developed as shown in Figure 26.

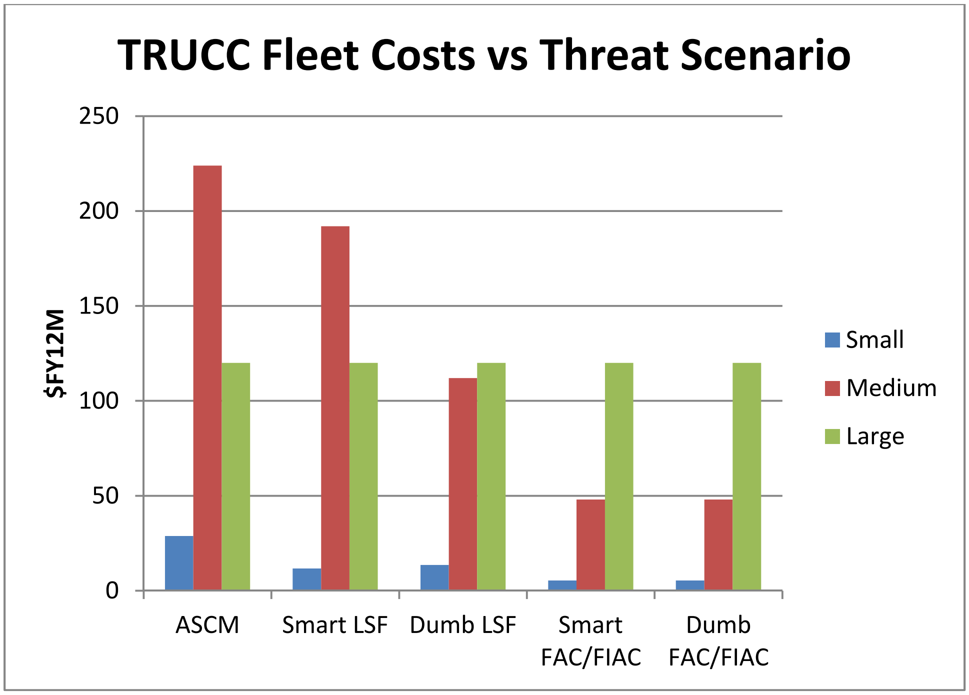

Figure 26. TRUCC Fleet Costs vs. Threat Scenario

This shows that the most efficient platform, from a pure procurement cost perspective, depends on the mission at hand, as well as the DRM. Small TRUCCs appear cost efficient; however, this ignores some of the limitations of these vessels. For the given Straits of Hormuz DRM, the Small TRUCC is capable of executing the mission only with multiple mid-mission refuelings. If the given DRM had shorter ranges, then the Small TRUCC would be the clear cost winner. The Medium TRUCC exhibits the lowest cost, given the endurance constraints of the Straits of Hormuz DRM. As explored by the Mission Vehicle group, placing missiles on the Medium TRUCC could further spread this cost efficiency across the ASCM and Smart LSF missions, further increasing the cost efficiency of the Medium TRUCC.

B. COST ESTIMATION IN DEPTH

Cost estimation was conducted including the total required force structure Operational Availability, as well as the probability of mid-mission failures. In this case, probability of success was defined as at least a 95% probability of fielding the minimum required number of TRUCCs to disable the enemy. By combining the Binomial curves and Ao numbers generated by the Operational Availability group, the minimum number of TRUCCs required to achieve a 95% probability of mission completion is shown in Table 16.

Table 16. TRUCCs Required for 95% Mission Completion

TRUCCs Required for 95% Probability of Mission Completion			
Threat	Small	Medium	Large
ASCM	36	16	4
Smart LSF	15	14	4
Dumb LSF	17	9	4
Smart FAC/FIAC	7	4	4
Dumb FAC/FIAC	7	4	4

The costs associated with this total required force structure is shown in Figure 27.

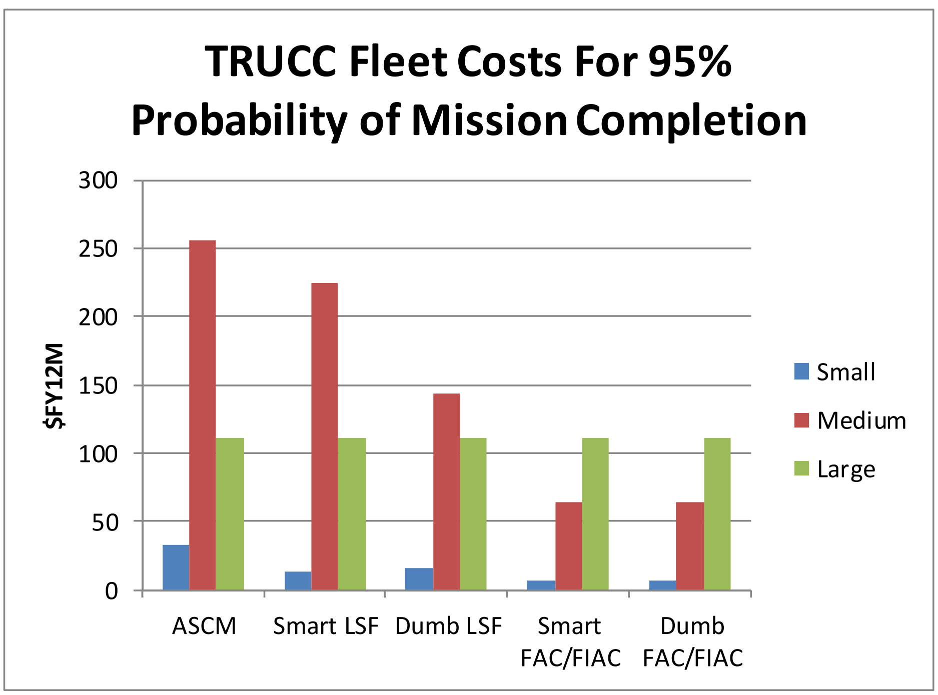

Figure 27. TRUCC Fleet Costs for 95% Probability of Mission Completion

The Ao and reliability values did not change the relationships between vessel cost and mission accomplishment. The major impact was to raise the costs of each system-of- systems in a roughly proportional manner.

For the purposes of exploration, if the Medium TRUCC was armed in accordance with the alternative arming scheme i.e., it was equipped with a directional missile launcher, the cost savings is significant, as shown in Figure 2.

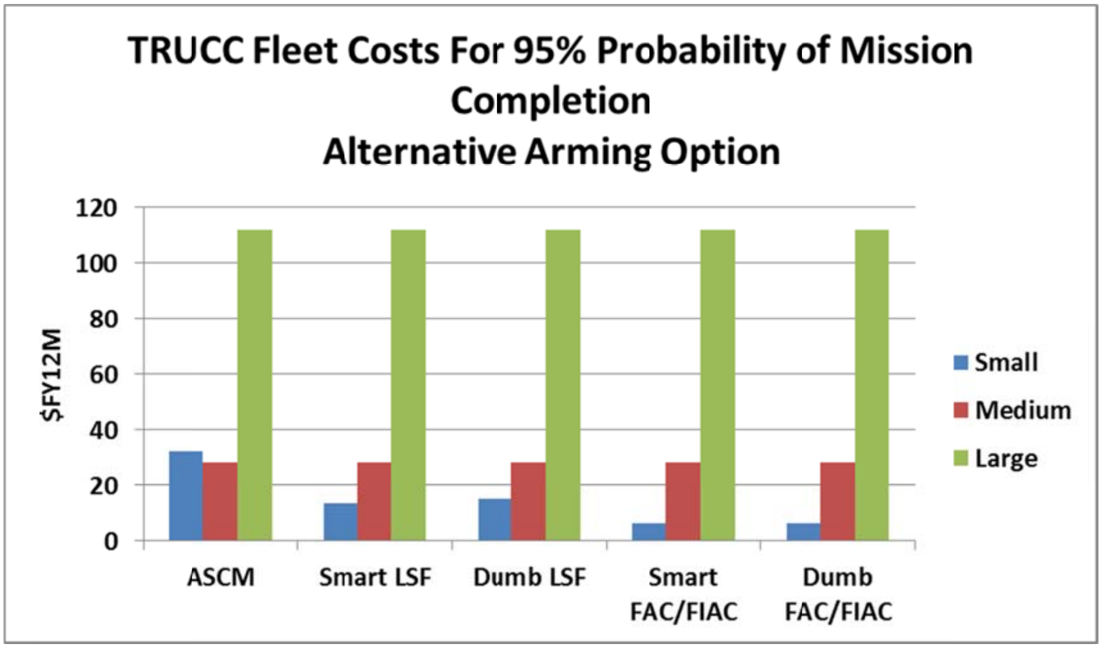

Figure 28. TRUCC Fleet Costs for 95% Probability of Mission Completion Alternative Arming Option

By generating cost savings across all mission areas, the efficiency of placing missiles on the Medium TRUCC is clear, as long as the detail-level design is consistent with the high reliability required for USV employment.

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VIII. ANALYSIS OF ALTERNATIVES

A. OVERVIEW

An Analysis of Alternatives (AoA) is defined as an analytical comparison of the operational effectiveness, cost, and risks of proposed materiel solutions to gaps and shortfalls in operational capability. AoAs document the rationale for identifying and recommending a preferred solution or solutions to the identified shortfall(s).[25]

B. ANALYSIS OF ALTERNATIVES

The team investigated and considered many different possible alternatives when conducting this analysis. In the end only one was chosen for further analysis. The initial alternatives considered were:

- Air assets
- Littoral Combat Ships (LCS)
- Manned small boats
- Guided Missile Destroyers and Guided Missile Cruisers

1. Air Assets Alone to Protect the HVU for the DRM

The term air assets includes all manned aircraft, all unmanned aircraft, and a mixture of both manned and unmanned aircraft. This was not a practical alternative because:

- It requires a dedicated aircraft carrier in the region or a squadron stationed close by
- An aircraft carrier requires capital ship escorts on station for the duration of the mission

[25] (MITRE Corporation, 2011, p. 1)

- There is a limited number of aircraft carriers
- Alternatively, this approach would require development and fielding of a UAV aircraft carrier

2. Deploying an Entire Squadron to the region

The use of a squadron of combat aircraft is possible and could be sustained throughout the DRM, but was not a practical alternative because:

- There are difficulties with access to air space in and around the Straits of Hormuz
- Combat aircraft are highly effective against FAC/FIAC and LSF threats, but provide limited defense against ASCMs

3. LCS to Protect the HVU

This approach might provide adequate protection against the FAC/FIAC threat, but it was not practical because:

- It provides little protection against the LSF and ASCM threats
- It is a single-mission focused platform (Anti-submarine Warfare, Mine Warfare, and Surface Warfare) and is not designed to operate in high-intensity air threat environments[26]

4. Manned Small Boats to Protect the HVU

These might provide adequate protection against the FAC/FIAC, but was not practical because:

- They provide little protection against the LSF and ASCM threats
- This approach requires surface to air missile capability for LSF and ASCM threats. This was ruled out due to the high risk to personnel onboard from

[26] (Baggett, 2008, p. 40)

noxious fumes and burns due to missile exhaust. For this reason, the use of manned small boats was not considered for further analysis.

5. DDGs and CGs to Protect the HVU

These warships are curently being employed in this manner and have sufficient capability against the FAC/FIAC, LSF, and ASCM threats. For these reasons, the use of DDGs and CGs was selected for further analysis. This analysis and how it compared to that of the TRUCCs is detailed in the following paragraphs.

C. ANALYSIS OF ALTERNATIVES “BACK OF THE ENVELOPE” OVERVIEW AND DEVELOPMENT

The project team developed a “Back of the Envelope” (BOE) model using Microsoft Excel® to compare and contrast alternatives to the TRUCC. The model was designed to determine the number of manned assets required to successfully kill all threats to a HVU.

The BOE was comprised of two portions: (1) Threat range to target position and (2) Number of assets required in order to ensure HVU survival. The first portion used assumptions about threat and asset weapons as inputs. They included:

- Range of the threat
- Velocity of threat
- Range at which the threat is detected
- Maximum intercept range for the asset weapon
- Minimum intercept range for the asset weapon
- Velocity of asset weapon
- Time between asset weapon launches
- Process time prior to the launch of the first asset weapon

The model then calculated five output parameters:

- Time to threat impact
- Time at which the threat would be detected
- Earliest asset weapon launch time
- Latest asset weapon launch time
- Maximum number of asset weapon launches

The purpose of the second portion was to determine the number of unmanned assets required for HVU survival. The following were inputs to the second portion of the model:

- Number of inbound threats
- Probability of intercept of the asset weapon
- Probability of kill of the HVU and asset given it was hit
- Assumed radar cross section (RCS) relationship of the HVU and assets
- Number of HVUs and assets
- Total number of asset weapons available
- Probability that the threat intercepts an asset or HVU given targeted

The model then calculated five outputs:

- Number of inbound threats
- Number of threats successfully intercepted by the asset weapons
- Number of leakers that got past the asset weapons
- Number of leakers targeting the HVU
- Number of HVUs destroyed

500 independent runs were simulated and the results compiled. The number of assets was incrementally adjusted to achieve 100% HVU survivability.

D. ANALYSIS OF ALTERNATIVES ASSUMPTIONS AND RESULTS

Guided Missile Destroyers and Guided Missile Cruisers were used as alternatives to the TRUCCs with the following weapons:

- Vertically launched standard missiles for the ASCM and LSF threats
- Five .50-caliber machine guns (50 Cal) and one “Bushmaster” cannon (25 mm) for the FAC/FIAC threat

These warships are the primary vessels currently providing escort and point defense for HVUs and are expected to be in service according to the 30 Year Shipbuilding Plan.[27] Assumptions were necessary within the model to accurately compare the TRUCCs to the manned vessels and were representative of those made for the TRUCCs within the initial DRM.

1. Anti-Ship Cruise Missile and Low Slow Flier Threats

In accordance with the previous mission effectiveness modeling effort, the following parameters were used for the ASCM and LSF threat.

- Initial range to threat: 80,000 yards from HVU
- Cruise altitude: 50 ft. above Mean Sea Level (MSL)
- Cruise speed: Mach 3 for ASCM; 111 m/s for LSF

Parameters for the DDG, CG, SM-2 and VLS parameters were obtained from unclassified open-source databases.[28] The radar cross sections (RCS) of the HVU, DDG, and CG were determined by using a ratio between the average lengths, widths, and displacements of the vessels, using the DDG as the baseline as seen in Table 17 and Table 18.

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[27] (Deputy Chief of Naval Operations (N8), 2012, p. 24)

[28] (FAS Facts, 2010, p. 1)

Table 17. DDG, CG, and Merchant Vessel Dimensions

Ship	Length (ft)		Average Length	Width (ft)		Average Width	Displacement (Tons)		Average Displacement
DDG	505	513	509	66	66	66	8,300	9,217	8,759
CG	567	567	567	55	55	55	9600	9,600	9,600
Merchant	1315	1230	1272.5	187	206	196.5	170794	273550	222,172

Table 18. DDG vs. CG (top) and DDG vs. Merchant Vessel (bottom)

DDG vs CG			
Length	Width	Displacement	Average
1.11	0.83	1.10	1.01
DDG vs Merchant ratio			
Length	Width	Displacement	Average
2.50	2.98	25.37	10.28

The gathered data and the ratio data are shown in the following tables. The number of 60 incoming cruise missiles was derived from the previous DRM and models used for the TRUCC.

Unfortunately, open source information referencing the detection capability of the SPY-1B/D radar was scarce and extremely unrealistic for the AEGIS Weapon System (AWS) and Vertical Launching System. Consequently, the following assumptions were made:

- SPY-1B/D maximum threat detection range of 24,000 yds against and ASCM and 16,000 yds against a LSF
- 80,000 yds maximum intercept range and 4,000 yds minimum intercept range with a speed of Mach 3.5 for the SM-2;[29]
- Eight seconds for the AWS to establish a track on the threat(s), process the incoming threat(s), and have the shipboard personnel make the decision to engage it with an SM-2(s) within hostile environment when weapons condition “red and free” is set.

[29] (FAS Facts, 2010, p. 1)

- Two-second time delay between SM-2 firings from the VLS; this represents the venting of any harmful or flammable gases from the VLS cells to allow the system enough time to process another launch.
- 0.95 probability of intercept of HVU by incoming threat.
- 0.7 Probability of intercept for the SM-2 (based on coursework at the Naval Postgraduate School and used in the absence of open-source or unclassified material)

The probability of killing the HVU given a hit remained at 1 to remain consistent with the DRM; however, using the survivability characteristics of the DDG and CG, the probabilities of kill given a hit were assigned 0.25 and 0.4 respectively.

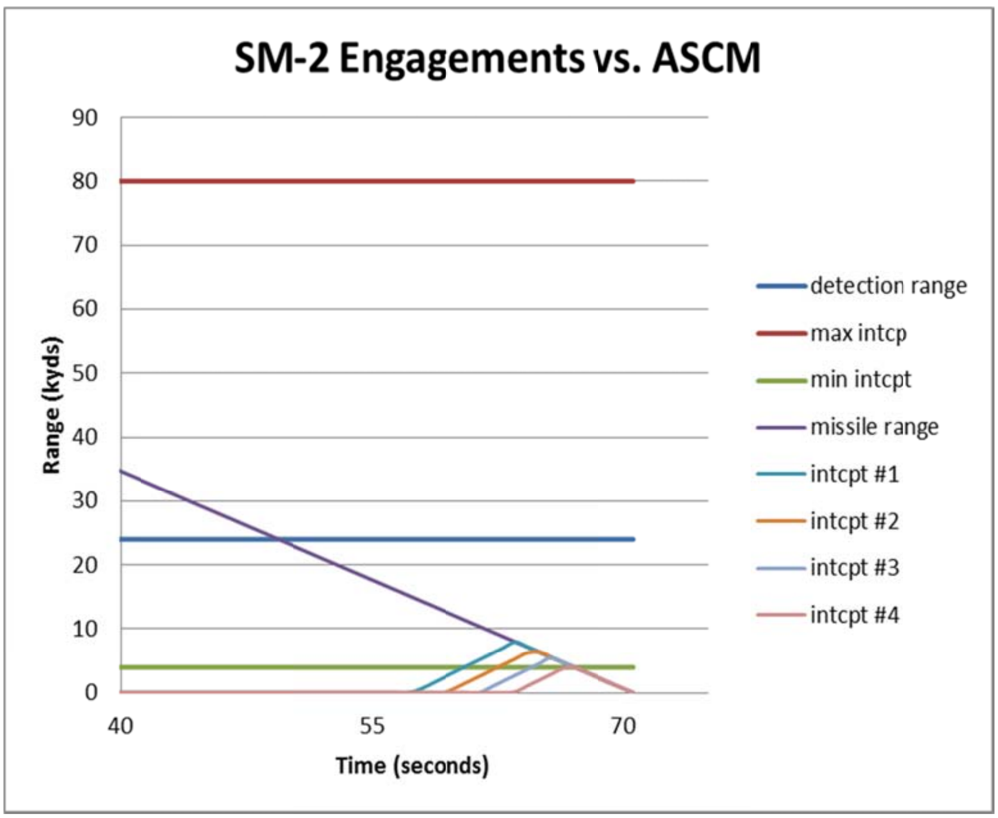

Figure 29. Cruise Missile vs. SM-2

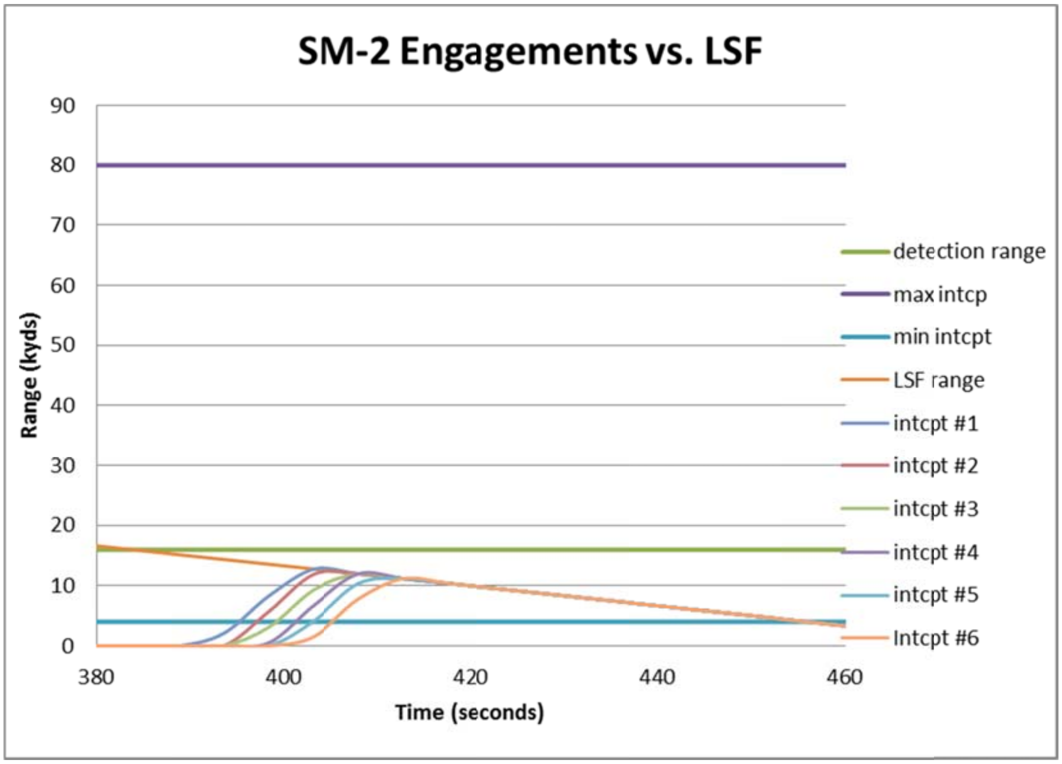

Figure 30. LSF vs. SM-2

a. Results

As depicted in Figure 29 and Figure 30, the ASCM threat results in 4 SM-2 engagements per warship against incoming missile and the LSF threat results in 31 SM-2 engagements per warship (NOTE: only the first six engagements are shown).

The BOE was restricted to the survival of a single HVU. The models considered a protection force comprised solely of DDGs or CGs and one of a DDG/CG mix (assuming performance parity). For the single-ship class model, 500 runs revealed the following number of ships vs. HVU survivability relationship (see Table 19):

Table 19. HVU Survivability Statistics

ASCM Threat		**LSF Threat**	
# of Manned Ships	HVU Survivability	# of Manned Ships	HVU Survivability
26	100%	4	100%
25	99%	3	89%
24	97%	2	0%
23	92%		
22	80%		

2. FAC/FIAC Threat

In accordance with the previous mission effectiveness modeling effort, the following parameters were used for the FAC/FIAC threat.

- Initial range to threat: 40,000 yards from HVU
- Cruise speed: 40 kts
- Maximum detection range of 24,000 yds (approximately the visual line of sight)
- 25 mm maximum intercept of 2,700 yds and a minimum intercept range of 200 yds with a muzzle velocity of 3,609 ft/sec. and 200 rpm rate of fire[30]
- .50-cal maximum intercept range of 2,000 yds and a minimum intercept range of 200 yds with a muzzle velocity of 3,050 ft/sec. and a 550 rpm rate of fire

30 (Friedman, 2006, p. 2)

- 20 seconds for topside personnel to process the incoming threat(s) and engage with 25 mm and no delay for the 50-cal because the engagement was already in progress
- A 0.9 probability that the FAC/FIAC intercepts the HVU
- 0.001 probability of intercept for each individual round
- 0.005 probability of hitting a vulnerable area on the FAC/FIAC per five round burst[31]

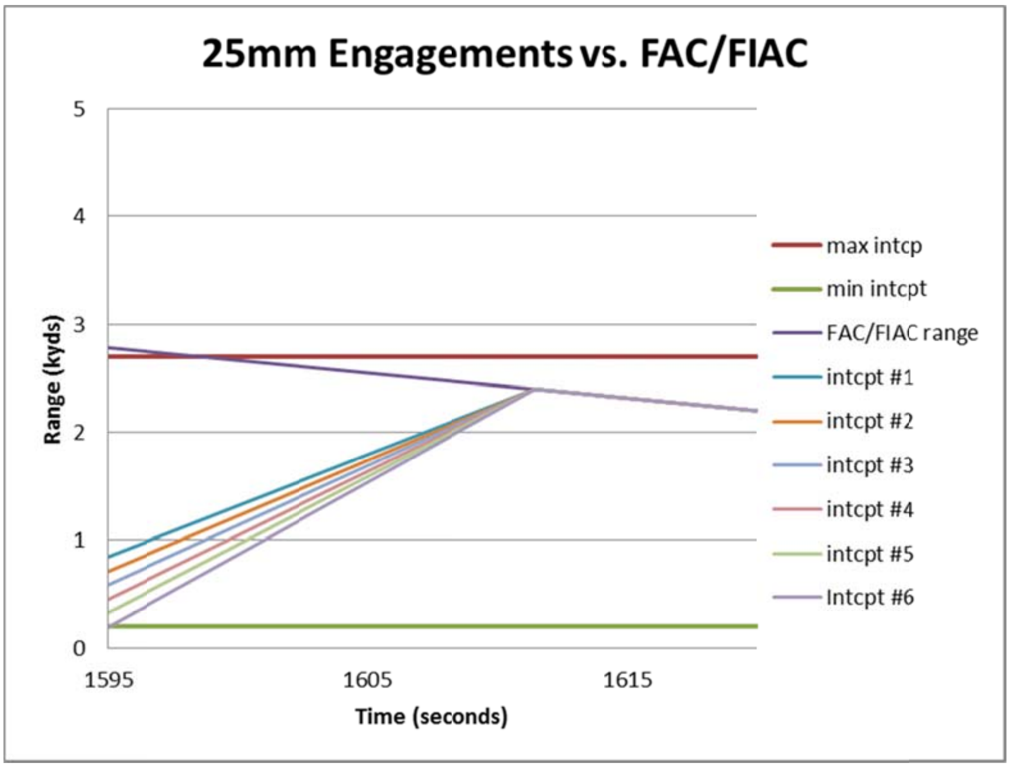

Figure 31. FAC/FIAC vs. 25 mm Machine Gun

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[31] (Harney, Proability of Kill given Burst , 2012)

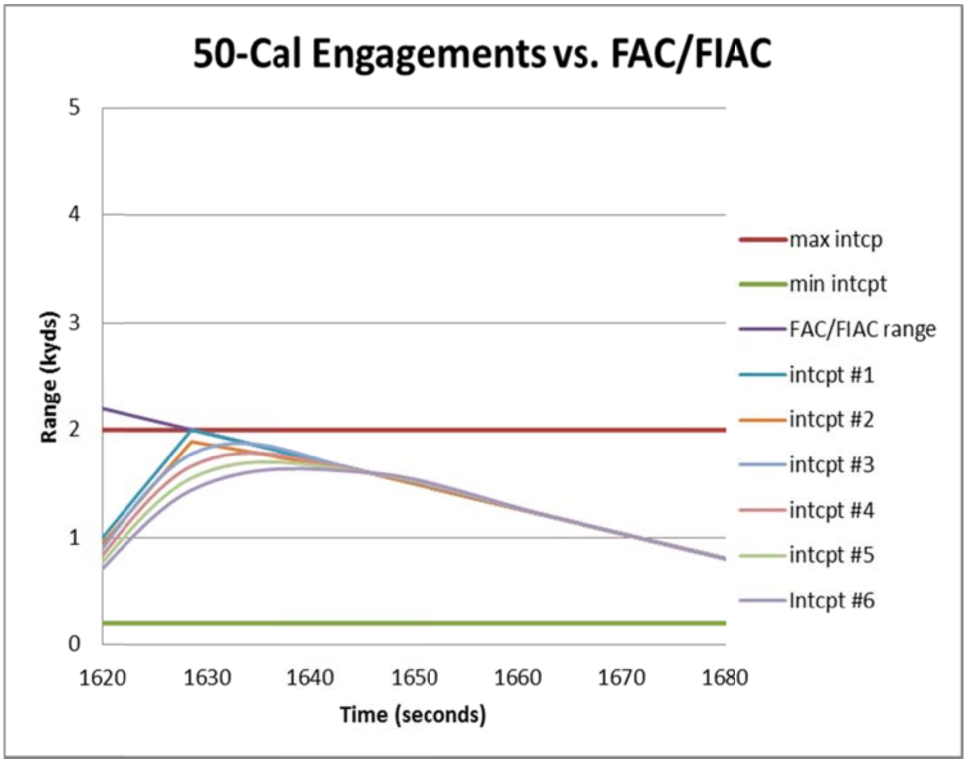

Figure 32. FAC/FIAC vs. .50 Cal Machine Gun

a. Results

The length of the FAC/FIAC engagement allowed for 4,673 rounds of combined 50-cal / 25mm ammunition available per ship to engage the incoming threats. The first six engagements for each weapon are shown in Figure 31 and Figure 32. Eighteen manned vessels were necessary to achieve zero losses to the HVUs as shown in Table 20.

Table 20. FAC/FIAC Threat HVU Survivability

FAC/FIAC Threat	
# of Manned Ships	HVU Survivability
18	100%
17	99%
16	96%
15	91%
14	76%

E. VALIDATION

This BOE was compared with the original model for the mission effectiveness design effort. The models for the TRUCCs and their respective alternatives yielded approximately the same results. This was achieved by reducing the threat detection delay associated with a manned platform and increasing the firing rate of the SM-2 matching all of the threat and weapon parameters used by the mission effectiveness modeling effort. The number of DDGs/CGs required to counter the ASCM threat was nearly identical to the number of TRUCCs required when the DDGs/CGs were configured with characteristics similar to the TRUCCs required by the mission effectiveness models.

The BOE was, by nature, a conservative estimate; it assumed the TRUCCs were co-located at a point location in the center of the target area. The MANA model produced more efficient results (i.e., fewer TRUCCs required) because of the screening tactics and cooperative engagement behavior of the

TRUCCs. This analysis confirmed that previous modeling efforts were sound and the BOE model is valid.

F. SUMMARY

DDGs and CGs can successfully perform the escort mission from our DRM against all of the considered threats. Chapter seven reveals the specific details regarding the elevated costs associated with DDGs and CGs conducting the ASCM mission. Figure 33 represents the difference in costs between the three variants of TRUCCs as compared to the major surface combatants. TRUCC costs are shown inset to enhance readability, because the cost of the required TRUCC fleet is two orders of magnitude less than the procurement cost of DDGs with comparable ASCM protection capability.

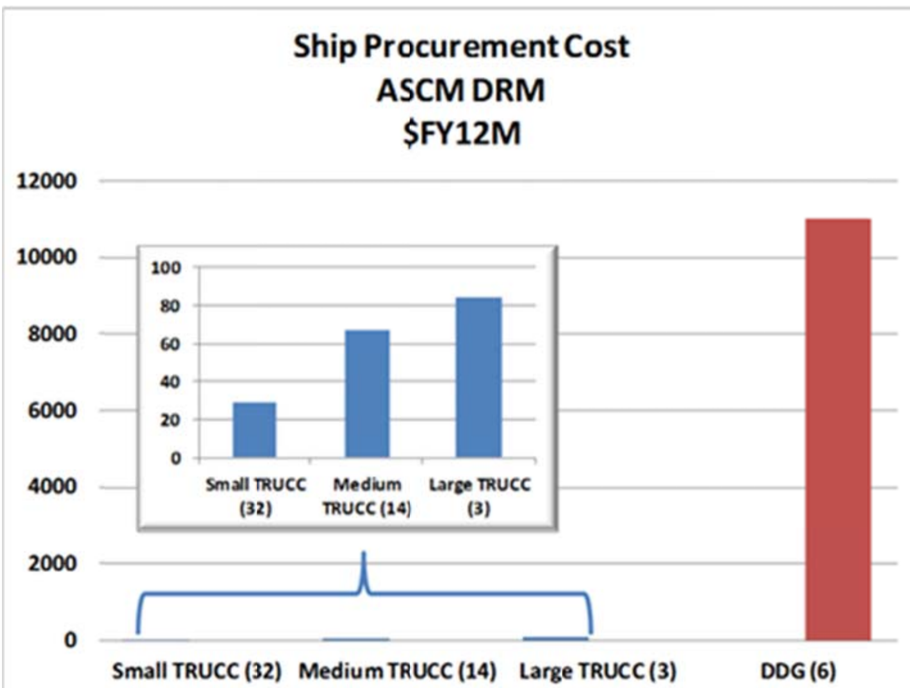

Figure 33. Ship Procurement Cost

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IX. ROADMAP

At the highest level, the roadmap is broken into three main operational concepts for control of USVs.

- Manual remote control of a single USV by a single human (one-to-one)
- Control of multiple USVs by one human operator (one-to-many)
- Completely autonomous operation of a group of USVs with no human interaction (full independence)

The operational concepts are sequential, meaning that the technologies required to execute the second concept require all of the technologies required for the first concept and so on. Any of the given DRMs can be executed utilizing any of these three types of control. For example, Multi-Threat Force Protection could be executed by a group of operators each controlling a single TRUCC. The coordination of the TRUCC defensive tactics would be akin to pilots in a section of aircraft coordinating an attack. Using one-to-many control, the TRUCC would execute many of the mundane functions (such as navigation) and only require user interaction to coordinate operations or provide by-exception direction as the attack unfolds. Using fully autonomy, the TRUCC fleet would act as a fully networked system-of-systems to provide for the defense of the HVU without human interaction.

The current state of existing capabilities places USVs at the early stages of the second operational concept. One-to-many control has been demonstrated, but the systems are in very early stages of development. The technologies required to achieve one-to-many control have yet to be fully developed. The technologies required to achieve the third operational concept are not available at this time, but it is likely that they will be available within the time scope of this report.

1. Manual Control of Single Unmanned Surface Vehicle (one-to-one)

With this technology, the user is able to remotely control a single Unmanned Surface Vehicle (USV). The ability to conduct remote non-mission-critical logistics transfer in a low-threat environment is an example of employing this capability in the future. As mission complexity increases, one-to-one control becomes more cumbersome and time delays increase (see Technical Compendium for full discussion). The technology required to support one-to-one control are shown in Figure 34.

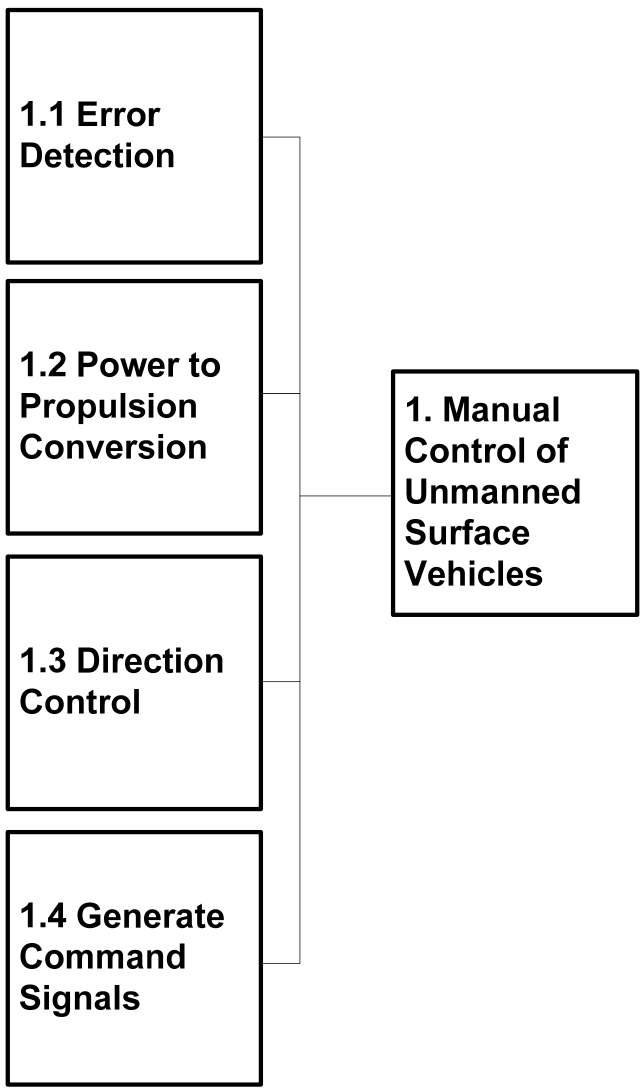

Figure 34. Manual Control of Multiple Unmanned Surface Vehicles

2 Control of Multiple Unmanned Surface Vehicles By-Consent/By-Exception (one-to-many)

With this technology, the user is able to remotely communicate with multiple USVs as they encounter unknown situations requiring direction from a human. The two forms of control in this operational concept are command by consent or exception. In command by consent, the USVs ask for controller permission before starting an action. In command by exception, the USV will conduct all actions unless the operator removes permission. An example of employing this capability in the future would be the ability to conduct mine clearance operations within a hostile environment. Mine clearance is a dull and dangerous task well suited for unmanned systems. In this example the network of USVs would be tasked with locating mines within a pre-established area. The USVs would continue to search the area without human direction until a mine is discovered, at which time the human would provide further direction to the network of USVs for neutralization of the mine. The technologies required for this capability are shown in Figure 35.

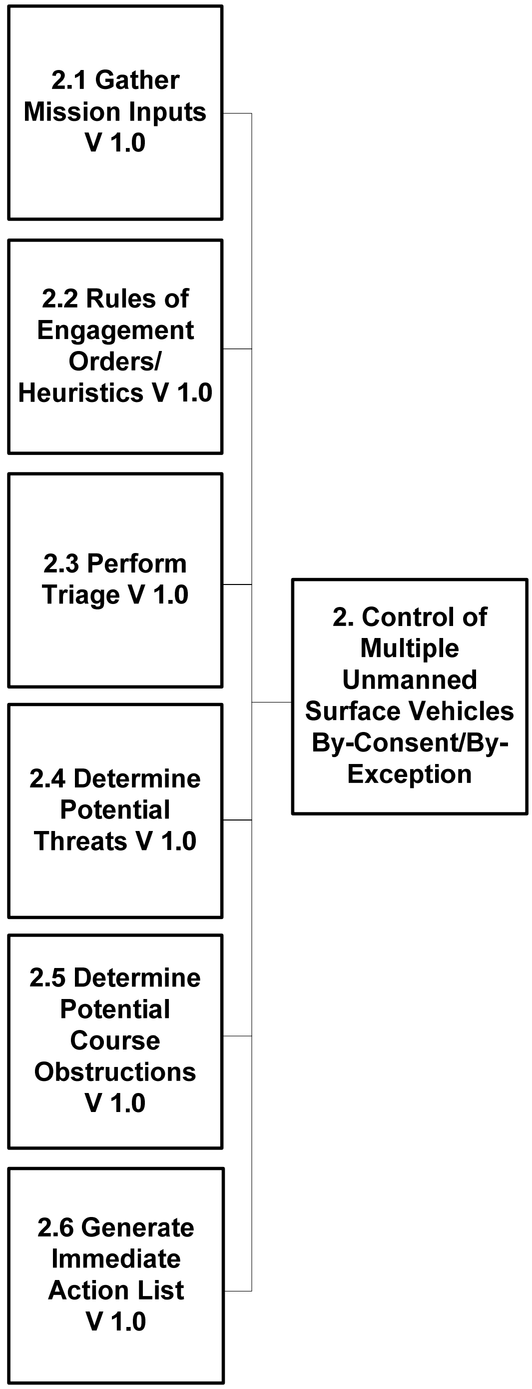

Figure 35. Control of Multiple Unmanned Surface Vehicles By-Consent/By-Exception

3. Autonomous Operation, No Human In/On Loop

With this technology, the TRUCCs are able to operate without human intervention. The TRUCCs are able to communicate to each other and other actors in the environment through wireless communications. Full autonomous operation offers significant combat capability by reducing latency, as detailed fully in the Technical Compendium. This is particularly important for complex combat environments, such as Multi-Threat Force Protection. It is possible to execute Multi-Threat Force Protection with one-to-one and one-to-many control; however, as combat complexity increases, human operators become overwhelmed resulting in unacceptable system latency. Reduced latency relates directly to increased combat capability of the TRUCC system-of-systems. The technologies required to achieve this capability is shown in Figure 36.

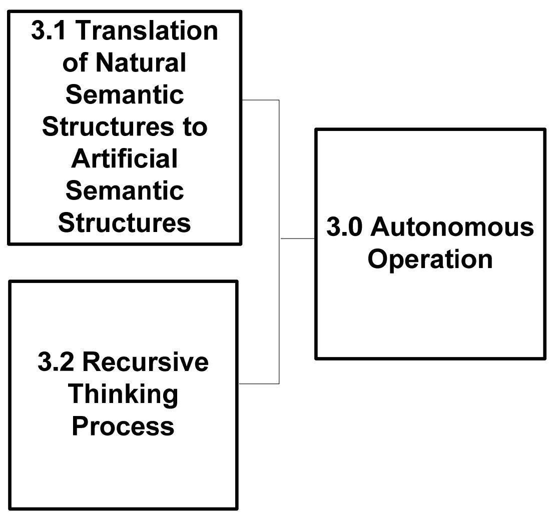

Figure 36. Autonomous Operation, No Human In/On Loop

4. Recommendations

Based on analysis of current technologies and capabilities there are several recommendations.

DOD should continue to invest and develop detailed rule sets for capabilities 2.1, 2.2, 2.3, 2.4, 2.5 and 2.6. The logic and low-level autonomy represented by these capabilities is still very immature. Improvements in these capabilities will increase the number of TRUCCs that can be effectively controlled by a single human operator. The examples mentioned in each section above are starting points for further research.

Investment in artificial semantic translation to support capability 3.1. The Technical Compendium covers several examples of research initiatives that demonstrate a standard mereology and ontology required for true translation.

Investment into research projects whose purpose is to determine the specific methods by which the human brain is able to operate to ensure the development of capability 3.2. There are several ongoing projects that have begun this development, as discussed in the Technical Compendium.

Begin the development of legal test cases to explore the ramifications of autonomous machines. Specifically the issues of foreseeable harm and tort liability are of concern for autonomous vessel operation. An example of a test case would be if the Google Autonomous Car were to crash into a fire hydrant. Legal processes must be in place to determine if the Google Corporation, the specific set of programmers, or some other entity, are culpable for the damage. At a higher level, policies must be in place to govern weapons release authorization for autonomous systems. If an autonomous machine kills a civilian, what are the ramifications to the system, the programmers and / or the supporting military unit? These complex legal and moral issues have significant ramifications for unmanned system development and should be examined concurrently with technology development.

Continue negotiations for creating an open architecture standard for connecting dissimilar machines. Though open architecture will not help in achieving the third operational concept, it will help near-term integration of developing systems. Integration managers can assist in this development, as discussed in detail in the Technical Compendium.

The financial development of the supporting technologies should be shared amongst several stakeholders. The Surface Warfare community, Mine Warfare community, USMC and amphibious forces have common interest in the development of these supporting technologies.

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X. CONCLUSION

This report proposes an operational concept for a family of Unmanned Surface Vessels that integrates with manned and unmanned systems to address a broad spectrum of missions. Unmanned Surface Vessels can be a force multiplier to the Fleet. Maximum impact of unmanned systems is realized when the force structure is defined through long-term analysis, as proposed in this report. A dedicated, long term, front-end analysis can provide increased combat efficiency and effectiveness for the future mix of manned and unmanned systems.

The primary focus for USV development should center on the littoral missions. The U.S. Navy is significantly vested in large multi-role ships for blue-water, long range missions. USVs executing littoral missions will free up the number of guided missile destroyers (and other assets) for blue-water missions, for which they are well suited. Additionally, the requisite high operational availability and mid-mission reliability necessary for the USVs can be achieved through shorter duration littoral deployments and access to forward-deployed maintenance facilities. This littoral operational concept is shown in the OV-1 diagram in Figure 12, which is reproduced here for convenience as Figure 37.

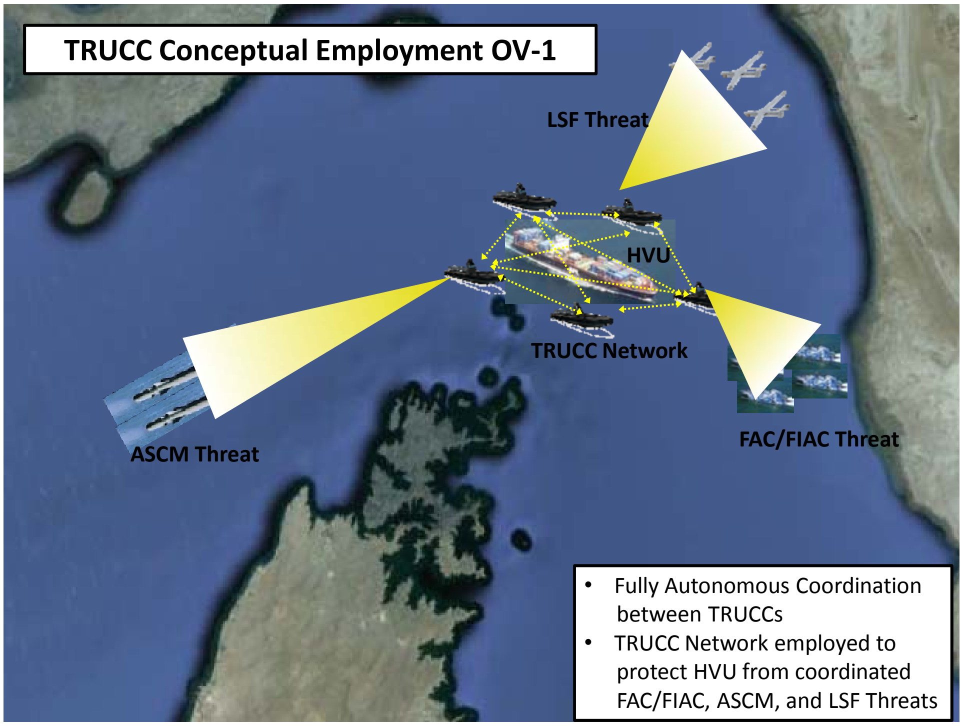

Figure 37. TRUCC Conceptual Employment OV-1

Mid-mission failures are critical elements of USV design. The loss of control of a USV at sea creates a multitude of problems for the unit-level operator and combatant commander alike, particularly when the vessel contains sensitive military technology and weapons. The reliability of these vessels should leverage best practices from communities with similar concerns, such as aviation and space systems. Utilizing high Ao and reliability factors typical of aviation systems reduces the force structure required for combat capability, as shown for a representative mission in Figure 38.

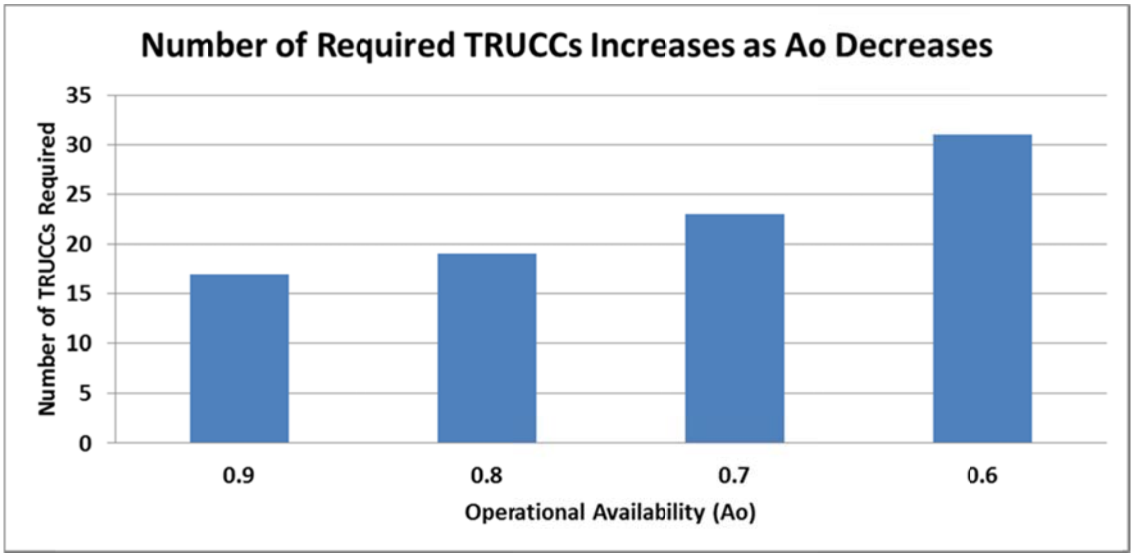

Figure 38. Number of Required TRUCCs Increases as Ao Decreases for Representative Combat Mission

The combat simulation and procurement cost estimation, coupled with the first-order analysis of alternatives, showed the cost benefits of the Medium TRUCC, particularly when coupled with a missile system, as shown in Figure 28, which is reproduced here as Figure 39. Note that Small TRUCCs are highly efficient; however, they are not suitable for a Straits of Hormuz DRM due to their low endurance.

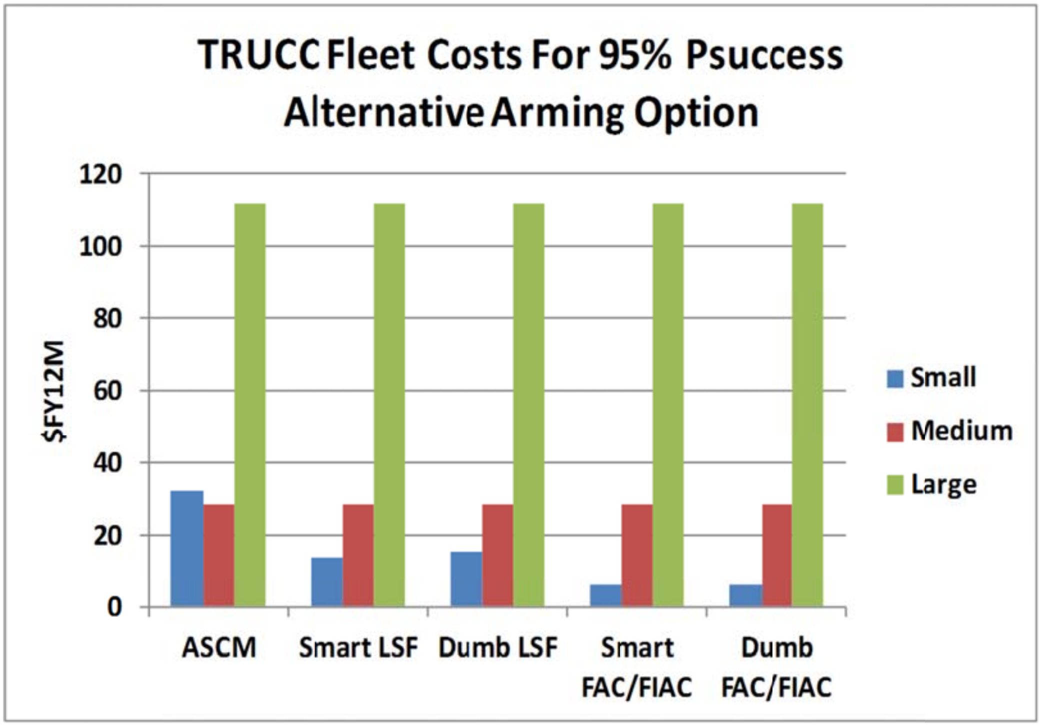

Figure 39. TRUCC Fleet Costs For 95% Psuccess Alternative Arming Option

The procurement cost for Medium TRUCCs to provide Multi-Threat Force Protection to the fleet is two orders of magnitude less than the cost of DDGs conducting the same mission, as shown in Figure 33, which is reproduced here for convenience as Figure 40.

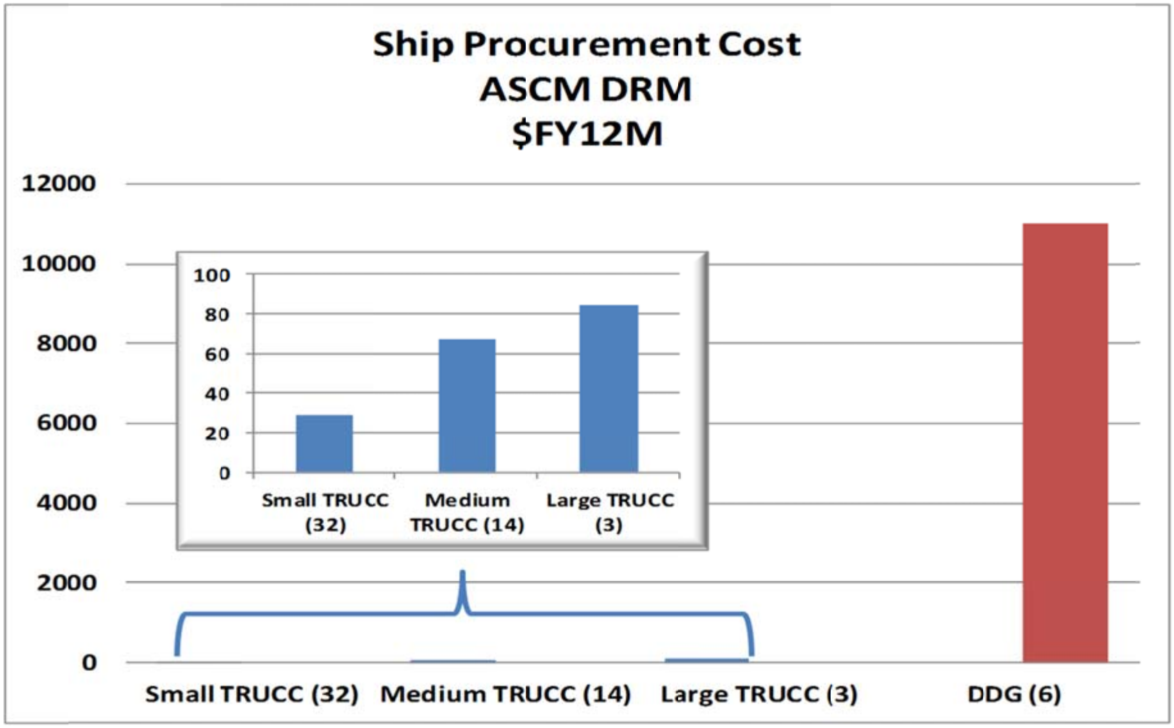

Figure 40. Ship Procurement Cost ASCM DRM $FY12M

The TRUCC does not serve as a replacement for multi-mission manned capital ships, but represents a significant return-on-investment to lower risk and increase availability of manned assets for other missions.

Model-Based Systems Engineering was used to simulate the Multi-Threat Force Protection combat scenario. Detailed analysis shows that the major factors for design of the TRUCC should consider the following to maximize combat capability:

- Number of TRUCC vessels (force ratio)
- Fast-firing, high Pk weapons, including missiles
- Open architecture and common interfaces to support minimal cost for weapon upgradability

Combat capability and true integration of the TRUCC with the manned force structure will not occur in the short term. Intermediate steps can facilitate incremental capabilities, as well as the mission requirements of disparate communities. These four design reference missions and their associated communities of interest will facilitate incremental funding over time, with an eye towards complete integration of manned and unmanned vessels in the 40–50 year timeline.

- Logistics: Surface Warfare, USMC/amphibious forces, Military Sealift Command
- Decoy transportation: Surface Warfare, USMC/amphibious forces
- Mine Warfare: Mine Warfare, Surface Warfare
- Multi-Threat Force Protection: Surface Warfare

The common functional capabilities to execute these missions all require research and development. All communities of interested in USVs should fund these core functional capabilities jointly to share in the costs and technological risk associated with autonomy development. Integrating existing technologies to demonstrate and field USVs with one-to-one remote control (i.e. one operator to one vessel) is possible in the near term. The technologies to support one-to-one remote control exist today; however, lack of funding and community support to integrate these technologies and demonstrate their capability is a major barrier to development of a TRUCC-like capability.

Mid-and-far term research is required for the development of the necessary recursive thinking processes and semantic translation (as defined in the Roadmap Technical Compendium) to support the ultimate goal of true independent unmanned vessel operation. This research should be actively conducted by agencies such as Defense Advanced Research Projects Agency, Office of Naval Research, and U.S. Naval Research Laboratory.

Development of USV operational concepts, such as the Tailorable Remote Unmanned Combat Craft, through front-end Systems Engineering analysis will pave the way for efficient development of a truly integrated manned-unmanned force structure through 2060 and beyond.

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XI. ROADMAP TECHNICAL COMPENDIUM

A. INTRODUCTION

The following roadmap is a description of technologies and capabilities required to facilitate TRUCC design and deployment. At the highest level, the roadmap is broken into three main operational concepts independent of mission as shown in Figure 41. The first is manual remote control of an USV by a human to conduct a designated mission. The second is the control of multiple USVs by one human operator. The final concept is the completely autonomous operation of a group of USVs with no human interaction. The operational concepts are sequential, meaning that the technologies required to execute the second concept require all of the technologies required for the first concept, and likewise for the third. These concepts and their supporting technologies are explained in greater detail in the following sections.

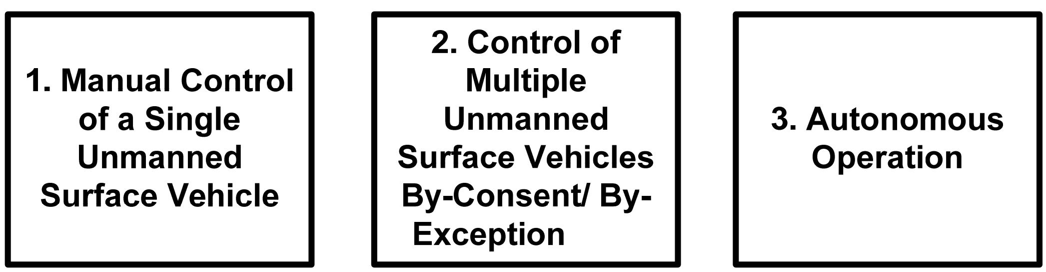

Figure 41. Roadmap Operational Concepts

Breaking down the development of the TRUCCs into these three operational concepts helps to show the effects of improvement to existing capabilities through technological improvements versus adding new capabilities through technological development. The metric used to compare the different operational concepts is *network externality.*[32] Network externality is a concept developed to describe the effects of information technology upon the value of a

[32] (Shankar, 2002)

product. This concept requires an increase in value as additional nodes are added to the system. An example of this effect is the telephone network. Initially, as more users or nodes are added to the network, the value of the telephone increases for all users because they are able to use it to contact more and more people. Facebook is another example. As more user pages are added, those using Facebook are better able to connect with their peers. Another aspect of network externality is the idea of *saturation*. Saturation occurs due to various reasons, but is evidenced when the addition of nodes no longer improves but rather decreases value. An example of a network that has reached saturation is the traffic system around Washington D.C. Initially the network of highways allowed for greater numbers of people to commute into and out of the city as required. As the number of people increased the road network reached saturation and the value began to decrease since the commute times for everyone increased.

By examining each of the different operational concepts it is possible to compare the point at which each reaches saturation and observe the value each paradigm represents. The definition of a node in each operational concept is different. The node in operational concept #1 is a human operator controlling a single TRUCC. For operational concept #2 a node is a human operator controlling several TRUCCs. For operational concept #3 a node is each TRUCC by itself; there is no human operator since they are autonomous.

B. OPERATIONAL CONCEPT #1

Each node added to the environment has a specified sensor range and associated weapon coverage. Within this defined area the human operator needs approximately 12.5 seconds to identify an incoming threat and activate a weapon if required.[33] If an overlap of weapons coverage occurs without the

[33] (Hardman & Colombi, 2010, p. 180)

required sensor coverage the first human operator can transmit the required information to other human operators for action approximately three seconds after the initial 12.5 seconds, as shown in Figure 42.

Node Definition: 1 TRUCC with Human Operator

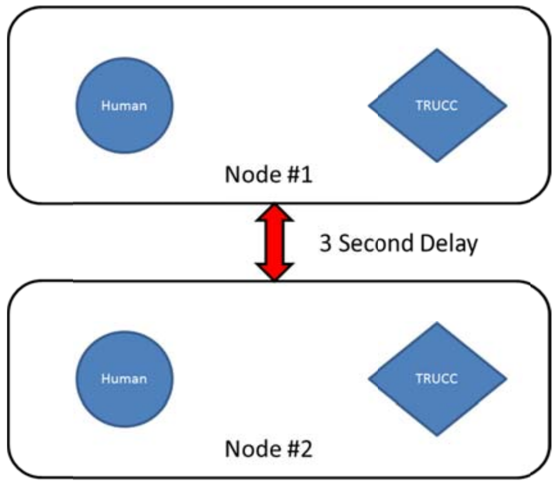

Figure 42. 1 TRUCC with Human Operator

As the number of TRUCCs increase, the area of sensor coverage increases until saturation is reached and the sensor ranges start to overlap. As the number of TRUCCs increases the area of weapon coverage increases until saturation is reached and the weapon ranges start to overlap. The number of parallel shooters depends on the spacing and weapons range of each TRUCC, and will increase proportionally to the amount of weapons overlap. The start time for the engagement begins when a target enters the sensor range for the entire network. The minimum delay for action from the start to the first action by an operator is 12.5 seconds. If another TRUCC is on the same threat axis, the earliest the other operator can act is some time greater than 12.5 seconds; this is due to the subsequent engagement process occurring in parallel with the first operator as the target enters the second TRUCC's sensor range. The minimum time to act for the operator(s) whose TRUCC is within weapon range of the target, but outside of sensor range, is 15.5 seconds.

Assuming perfect communication between humans, sensor range will increase proportionally with the increased number of TRUCCs and trend towards a constant value, but the number of parallel shooters will increase while delay for action of the entire network is 15.5 seconds. This is highly unlikely because the number of humans increases proportionally as more TRUCCs are added and the delay in transmitting the targeting information to the TRUCCs within weapons range will increase. Due to this, there is a point where the number of parallel shooters will not increase because it will take too long to get the targeting information to them, at which point adding more TRUCCs is futile.

C. OPERATIONAL CONCEPT #2

As additional TRUCCs are added to this environment, the same effects occur as in case #1. The areas of sensor and weapon coverages increase until saturation. The key difference is the number of parallel shooters that can be added until the delays render them useless. The minimum time to engagement for any node in this case is still 12.5 seconds, as illustrated in Figure 43.

Node Definition: X TRUCCs per Human Operator

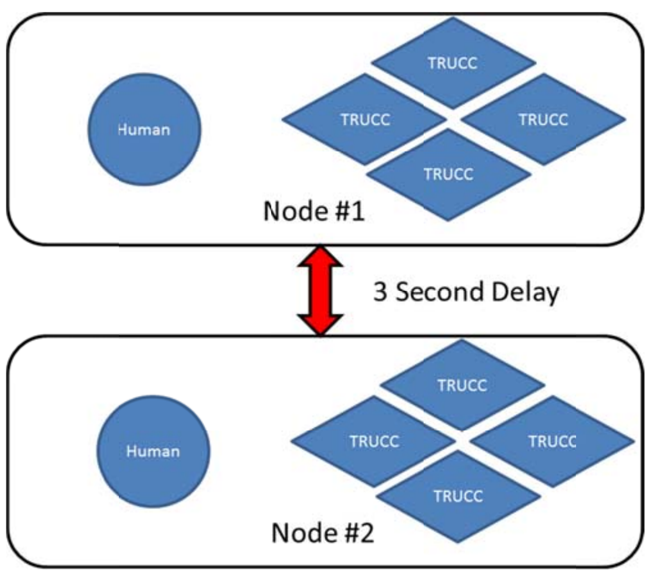

Figure 43. X TRUCCs per human operator

The difference is that if any other TRUCCs within the same node are within weapon range, the transmission time for targeting information is limited only by the processing speed of the TRUCCs. The three-second delay still exists if TRUCCs in another node are to be activated. Once the second node is activated, all available TRUCCs have the ability to become parallel shooters without any additional delay beyond that required for the human-to-human data transmission. Saturation of effective parallel shooters will still occur; however, the final number of shooters is higher than in Case #1 because each node represents more TRUCCs available for engagement.

Two other effects will help determine where the saturation point occurs:

- As additional nodes are added to the network, the bandwidth requirements will increase. If there is not enough bandwidth available to transfer the targeting information between nodes or within nodes, the number of parallel shooters will be limited.
- The human-to-machine interface efficiency; in this case a human is providing some decision-making input to the node. If the number of TRUCCs an operator is controlling becomes so large that he or she cannot effectively process the volume of information, the delay for taking action will increase the saturation level of shooters.

D. OPERATIONAL CONCEPT #3

In this case the node that is closest to the target will conduct the detect-to-engage sequence. The minimum delay is 12.5 seconds assuming the machine is as capable as a human. The number of parallel shooters is limited only by bandwidth as nodes are added to the system, as illustrated in Figure 44.

Node Definition: A Single Autonomous TRUCC

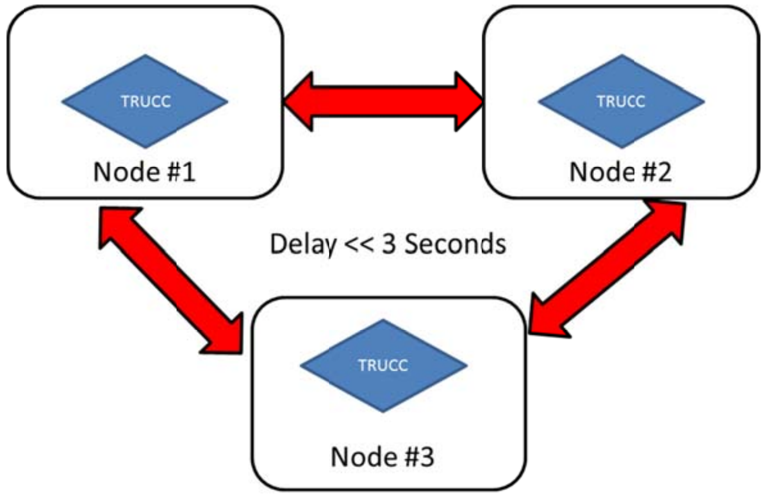

Figure 44. A single autonomous TRUCC interaction

Once the first TRUCC has the targeting information, the transmission is limited only by the processor speed of the TRUCC and available bandwidth. The number of nodes required before saturation occurs is extremely high, because the human delay of 3 seconds to transmit information between nodes does not exist.

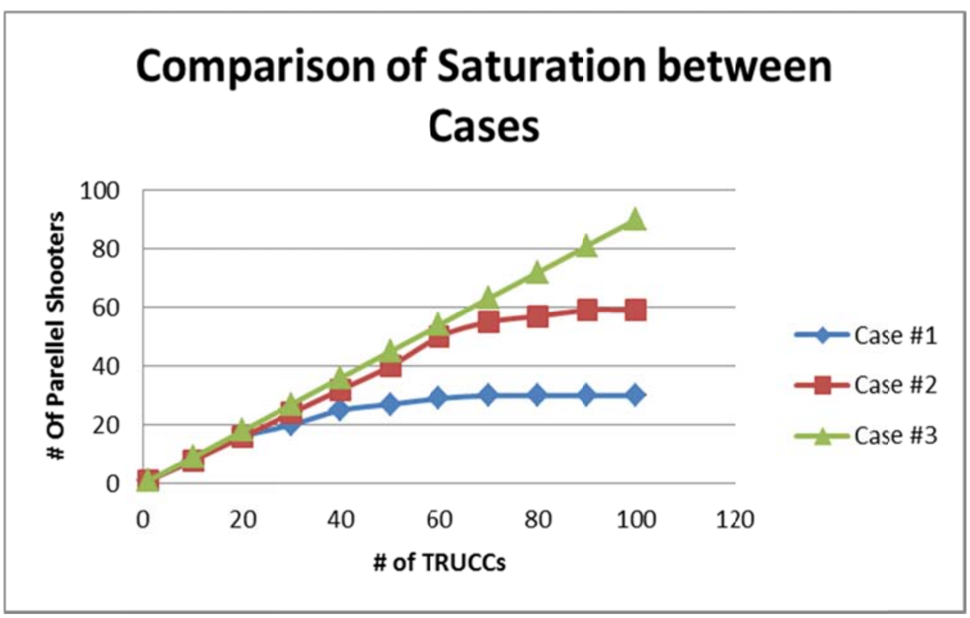

Figure 45. Comparison of Saturation between Cases

Figure 45 indicates the possible advantages between the different operational concepts. The point at which saturation occurs is different for each case. The saturation point of the network indicates the maximum possible benefit that an operational concept can achieve. No matter how many nodes you have using the Operational Concept #1 the maximum number of parallel shooters is thirty. When Operational Concept #2 reaches saturation there are sixty parallel shooters. The difference between the two concepts shows the added value of Operational Concept #2. Figure 38 depicts the relationship between hypothetical data representing an estimation of saturation for the different operational concepts. Further investigation and experiments of developing systems must be conducted in order to develop the true shape of these curves and therefore their relative value to the decision makers

E. TIMELINE OF TECHNOLOGY DEVELOPMENT

The current state of existing capabilities places USVs at the early stages of the second operational concept. The control of multiple USVs has been demonstrated but the systems are in very early stages of development. The maximum human-to-USV control ratio has not been achieved. The technologies required achieve the third operational concept are not available at this time, but it is highly likely that they will be available within the next five decades.

F. SUPPORTING TECHNOLOGY DEFINITIONS

1. Data Storage Capacity: Sufficient data storage capacity and speed of access and retrieval to support the TRUCC system when given commands from the remote operator and internal processes.

2. Computer Processor: Sufficient speed for the network of TRUCCs to collect, process, and take required action within a human-equivalent time period, while ensuring timely and proper mission inputs are collected. Associated with the processor is the architecture, language, manufacturing process feature size, and chip yield.

3. Common Operating Language between the TRUCC and the Remote Operator: Communications in the same language to include localized definitions in order to fulfill this requirement without requiring additional translation software within the system.

4. Wireless Communication Network: Sufficient bandwidth to support wireless communication within and from the network of TRUCCs. Communication from the TRUCCs is critical as recommendations are reported to the operator in order to take action.

5. Rule-based Alarm Criteria: A list of actions within the system software including the ability to monitor, identify and report normal/abnormal states within the TRUCC/operator network.

6. Status Monitoring Sensors: Sensors available to monitor the required systems within the TRUCC: Hull, Mechanical, and Electrical (HME) components of the TRUCC as well as the installed mission specific modules for errors providing real time system status to include correct position of the TRUCC in relation to a known geographic position as well as other TRUCCs within the network. Data validity is a current issue with sensors which must be addressed, including latency of data as well as the system having knowledge of what sensor data is needed.

7. Propulsion Technology: Propulsion technology is currently available which will satisfy mission requirements in both endurance as well as speed.

8. Rule-based Decision Method Criteria: A list of actions within the system software to include the ability to control, collect, process, and take action on data from the network of TRUCC's antennas, sensors, weapons, and other mission required peripheral devices to determine the appropriate course of action.

9. External Sensors: Sensors available to collect system required information using installed peripheral devices, as well as the collection of data provided by other vessels within the network of TRUCCs in order to support the

TRUCC mission. A few examples of the required sensors are communication antennas, Global Positioning System (GPS), Infrared Radiation (IR), Optical and other sensors which will provide the network of TRUCCs with sufficient situational awareness for timely and accurate mission input data. Data validity is a current issue with sensors which must be addressed, including latency of data as well as the system having knowledge of what sensor data is needed.

G. HIGH LEVEL DEPICTION OF CAPABILITIES

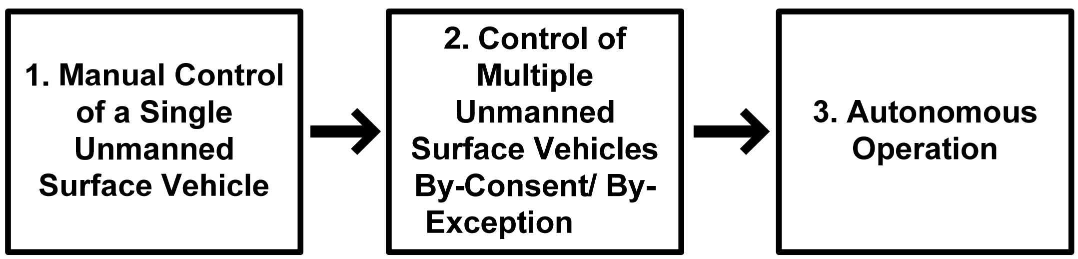

Figure 46. High-Level Operational Concept Flow Chart

The Higher-Level Depiction of Operational Concepts represents a flow of capabilities over time employed in parallel with the development of the TRUCC, as shown in Figure 46. The arrows between the concepts represent the formative development of technology from one capability to the next.

Each operational concept is supported by several lower-level capabilities. These lower-level capabilities require some combination of the supporting technologies discussed earlier. The lower-level depiction of capabilities focuses on the key capabilities required for the TRUCC with the understanding that the trade space includes many other capabilities that have not been addressed due to time constraints within the project. The capabilities identified have been used to generate the roadmap for future TRUCC funding and development.

The following section breaks down each operational concept by its supporting capabilities. Each of the supporting capabilities is broken down into the supporting technologies. Due to the fact that some supporting technologies are applicable to several supporting capabilities they appear several times.

1. Manual Control of Single Unmanned Surface Vehicle

The capabilities required to achieve this operational concept are depicted in Figure 47. With this technology, the user is able to remotely control a single Unmanned Surface Vehicle. The ability to remotely conduct non-mission critical logistics transfer from one location to another within a non-hostile environment is an example future mission area for this level of technology and capability.

1.0 Supporting Capabilities

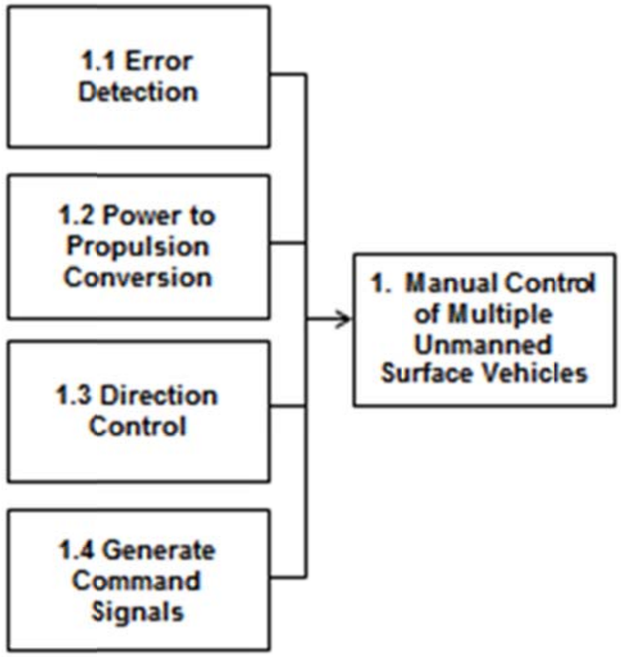

Figure 47. Manual Control of Multiple Surface Vehicles

a. Error Detection Capability

The technologies required to achieve this capability are depicted in Figure 48. The ability to monitor, identify, and report normal/abnormal states within a TRUCC module in the physical and information domains. This capability includes errors in the position of the TRUCC in the network of TRUCCs as well as error in its position with reference to a known geographical position.

1.1 Supporting Technologies

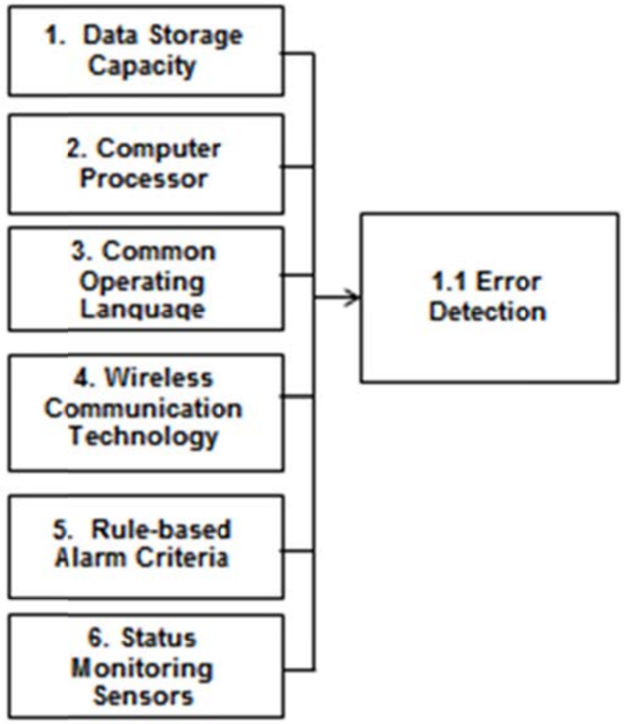

Figure 48. Error Detection

(1) Examples of Error Detection. The required technology is readily available to fulfill the function of error detection. The Java 2 Platform, Enterprise Edition (J2EE®) semantic programming language is an example of a fielded system demonstrating this capability.[34]

An example software application is available from Rhode and Schwarz and is called R&S RA-CM Continuous Monitoring Software. The Rhode and Schwartz systems operate wirelessly using a common operating language. The product includes the required processor as well as data storage

34 (Vawter, 2001)

required to meet system requirements. Rhode and Schwartz have an ISO-9001 certification listing the U.S. Government as a user of its systems.[35]

A second example of technology currently available to perform error detection is eiManager. This technology is currently employed in the highly dynamic and important Automatic Teller Machine network. Secure and timely communications is critical within this example of the function, and could be even more important within our network of TRUCCs in the area of anti-tamper and denial. The product is available through the Fiserv Corporation and includes certain error correction algorithms which may apply to the fleet of TRUCCs and are examples of error correction within a network.[36]

Another example of error detection with reference to the position of the TRUCC is the use of the Global Positioning System (GPS) to ensure proper TRUCC position to carry out the desired mission;[37] establishing the exact location of the vehicle is critical to detecting a location error.

The use of the Inertial Navigation System (INS) used to perform error detection in the position of the TRUCC in a GPS denied environment is yet another way to ensure the correct position of the TRUCC.[38]

(2) Demonstration Requirements. A software program will need to be designed to a sufficient level of reliability and accuracy to ensure this capability satisfies the TRUCC requirements.

(3) Policy or Ethics Issues. There are no ethics issues related to this capability. Policy issues with this technology may exist within the decision to select the programming language for use in the network of TRUCCs.

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35 (Schwarz, 2011)

36 (Jorgenson, 2010)

37 (US Government, 2012)

38 (T Xu, 2011)

b. Power-to-propulsion Conversion Capability

The technologies required to achieve this capability are depicted in Figure 49. This describes the ability to convert an energy source into motion of the TRUCC in order to satisfy directed mission requirements.

1.2 Supporting Technologies

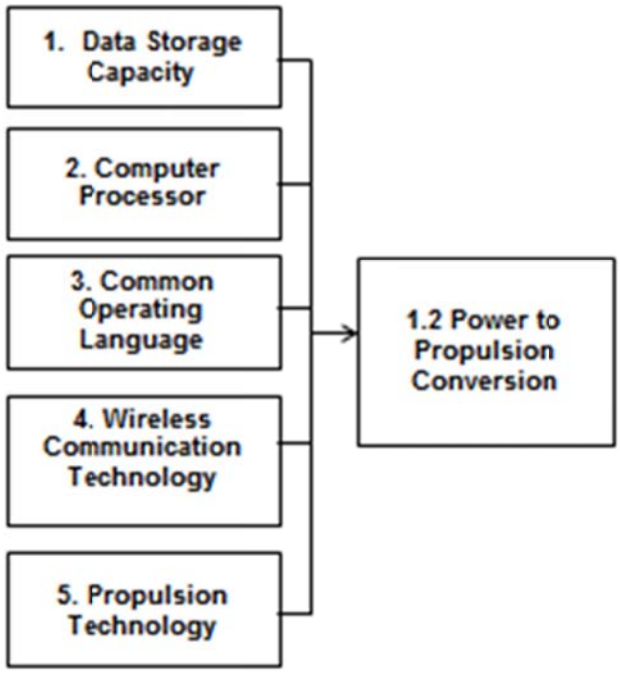

Figure 49. Power-to-propulsion Conversion

(1) Examples of Power-to-propulsion Conversion. An example of power propulsion conversion is the use of a marine diesel engine. Caterpillar© Corporation manufactures marine diesel engines currently used in the U.S. Navy, Army, and Marine Corps.[39]

A combination of solar, wind, battery, and diesel power are currently being used in a demonstration surface vehicle built by Solar Sailor Holdings Ltd. with assistance from the Australian government. This vehicle

[39] (Caterpillar Corporation, 2011)

operates in the Sydney Harbor as a ferry and operates using all four types of propulsion currently available.[40]

Fuel cell technology has been demonstrated on the Norwegian Sea supply ship Viking Lady, built by Eidesvik and its partners. They have installed a 320 kilowatt molten carbonate fuel cell which operates on liquefied natural gas to propel the 5,900 metric ton vehicle.[41]

(2) Demonstration Requirements. The requirement for power-to-propulsion conversion acceptance is such that the tested capability exceed TRUCC requirements by a yet to be determined percentage value before acceptance of this technology while meeting the designed to requirement of reliability.

(3) Policy or Ethics Issues. Significant ethical issues surround this technology; some of the major issues are the acceptance of future advances in energy generation and use due to environmental as well as economic concerns. There are significant policies issues regarding selection of power-to-propulsion technology. These issues include (but are not limited to), environmental concerns, allocation of government funding to private industry, and anti-trust concerns.

c. Direction Control Capability

The technologies required to achieve direction control capability are depicted in Figure 50. The ability to provide maneuverability by redirecting the fluid past the hull, thus imparting a turning or yawing motion to the TRUCC

40 (Solar Sailor, 2012)

41 (Almeida, 2012)

1.3 Supporting Technologies

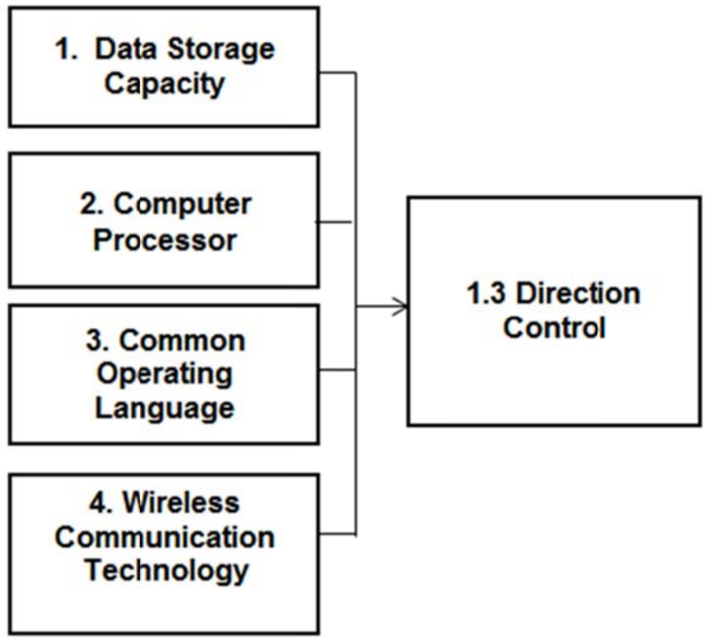

Figure 50. Direction Control

(1) Examples of Direction Control. :An example of direction control is the use of a water jet, Ultrajet®, manufactured by Ultra Dynamics Incorporated.[42] Water jets are currently employed in the U.S. Army and Marine Corps.

Another example of direction control is the use of a rudder positioning via an actuator.

(2) Demonstration Requirements. The requirement for direction control acceptance is critical to the success of the TRUCC. The delivery acceptance criteria must meet an extremely high level of reliability and accuracy in order to satisfy the TRUCC requirements.

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[42] (Ultra Dynamics, 2011)

(3) Policy or Ethics Issues. No policy or ethics issues are involved in the direction control of the TRUCC.

d. Generate Command Signals Capability

The technologies required to achieve this capability are depicted in Figure 51. The ability for the TRUCC to receive and translate remote operator commands into physical/nonphysical actions. The capability includes the ability to control multiple peripheral devices within the TRUCC to complete the desired mission. For example, the ability to control an optical sensor for Intelligence, Surveillance, and Reconnaissance (ISR) purposes while moving cargo from sea to shore, or the ability to remotely fire a gun system installed on the TRUCC platform are examples of this capability.

1.4 Supporting Technologies

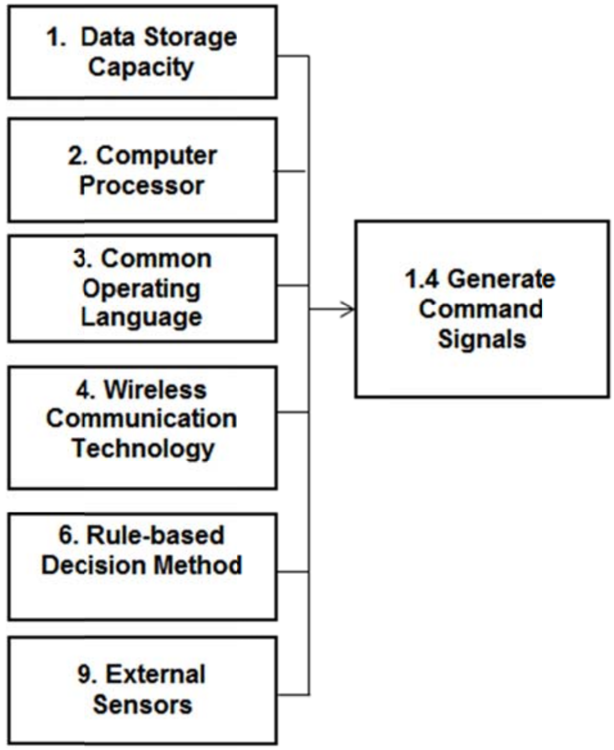

Figure 51. Generate Command Signals

(1) Examples of Generate Command Signals. The current use of the MQ-9 Reaper Unmanned Aircraft Vehicle (UAV) to locate targets and then engage with operators' remote command is another example of the ability to generate command signals. The United States Air Force's (USAF) Command Mission Control Center (CMCC) is a centralized or hierarchical Command and Control (C2) element for a collection of heterogeneous Unmanned Aircraft System (UAS). The CMCC supports a variety of operating systems and provides operating system flexibility between systems.[43]

[43] (Fick, 2012)

(2) Demonstration Requirements. The requirement to generate command signals is essential for the operator to be able to control the TRUCC. The delivery acceptance criteria must meet an extremely high level of reliability and accuracy in order to satisfy the TRUCC requirements.

(3) Policy or Ethics Issues. The ethics issue regarding the generating command signals rests in the worst-case scenario of an incorrect signal being generated and the operator taking action on the incorrect signal (e.g., fratricide or killing innocents). The major policy issue with this technology is resolving accountability for machines incorrect application of deadly force.

2. Control of Multiple Unmanned Surface Vehicles By-Consent/By-Exception

The capabilities required to achieve this operational concept are depicted in Figure 52. With this technology the user is able to remotely communicate with multiple USVs as they encounter unknown situations requiring direction from a human. An example of employing this capability in the future would be the ability to conduct mine clearance operations within a hostile environment. Mine clearance is a dull and dangerous task perfect for unmanned systems. In this example the network of USVs would be tasked with locating mines within a pre-established area. The USVs would continue to search the area without human direction until a mine is discovered, at which time the human would provide further direction to the network of USVs for neutralization of the mine.

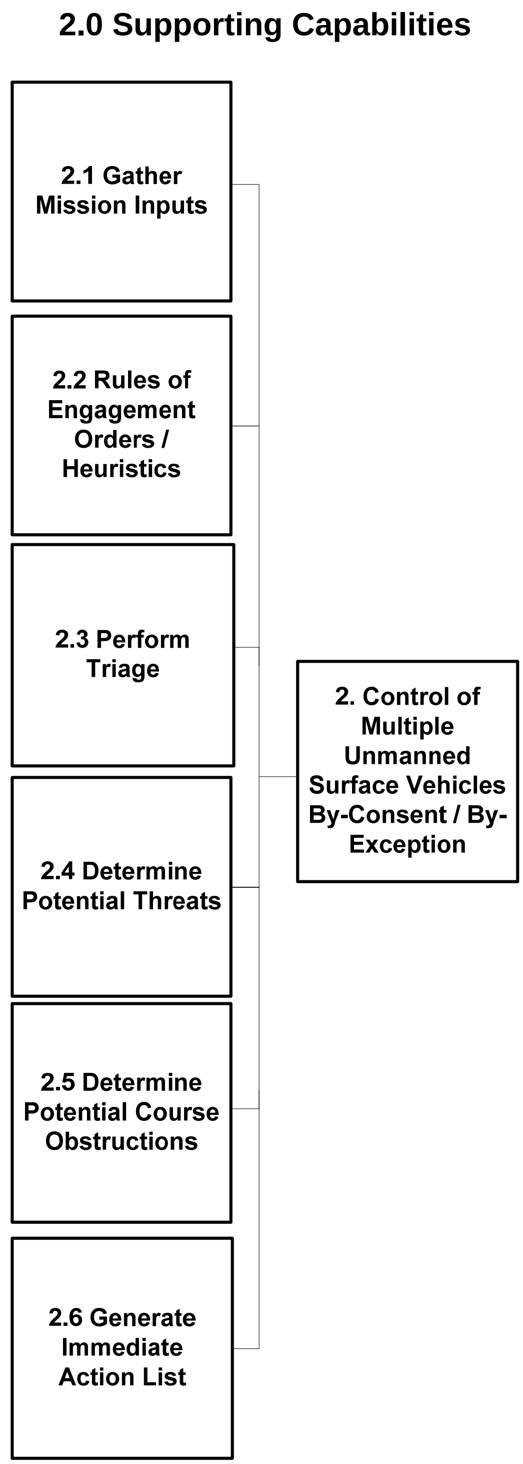

Figure 52. Control of Multiple Unmanned Surface Vehicles By-Consent/By-Exception

a. Gather Mission Inputs Capability

The technologies required to achieve this capability are depicted in Figure 53. The ability to collect and process all mission requirements in order to execute the desired mission. Mission requirements in this capability include navigation obstruction avoidance, following remote operator guidance, and ensuring the safety and survival of the network of TRUCCs at a near human-like speed.

2.1 Supporting Technologies

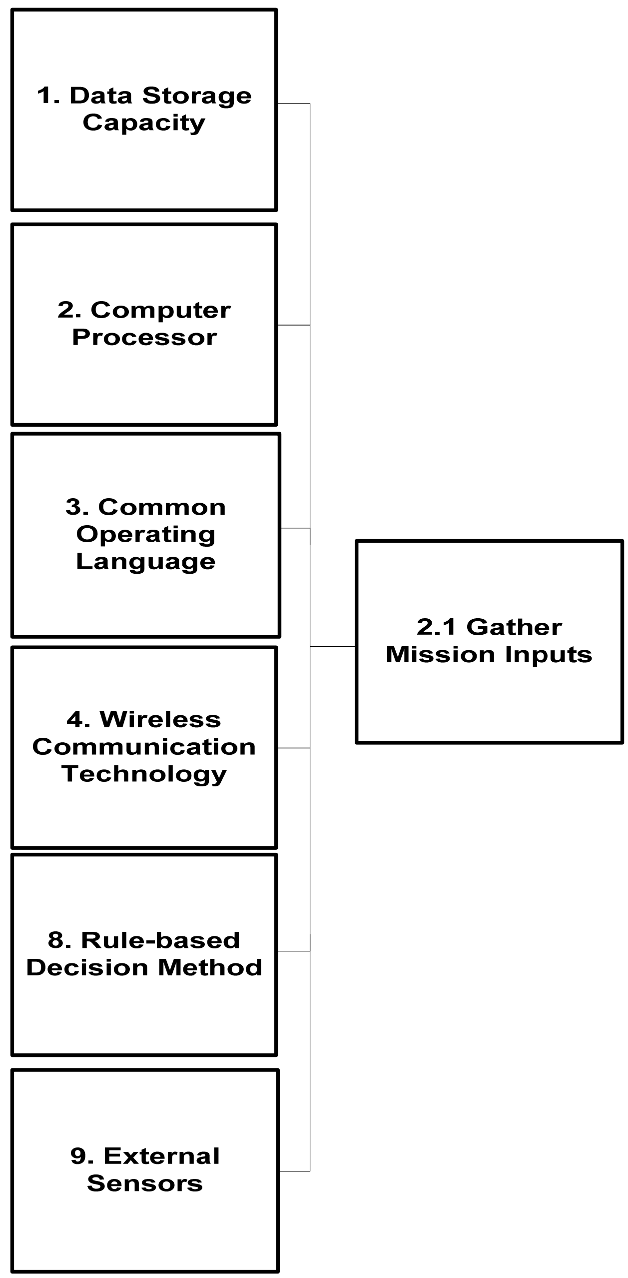

Figure 53. Gather Missions Inputs

(1) Examples of Gather Mission Inputs. An example depicting the capability of processing collected information is currently fulfilled at a low level of performance using software programs composed of multiple if-then

statements which will place the consequences in a priority queue awaiting corrective action. ColorForth semantic programing language employs this type of function and is available and released for unlimited use.[44]

The Fleet Class Common Unmanned Surface Vehicle (CUSV) built by Textron Systems has demonstrated the control of two unmanned surface vehicles by one operator and over 60 support personnel.[45] The CUSV platform employs AAI's command and control system. This system has the ability to gather, and process mission inputs successfully but has yet to be proven to do perform this at a near-human speed.[46]

(2) Demonstration Requirements. In order to ensure this capability satisfies the TRUCC requirement a software program will need to be designed to a sufficient level of reliability and accuracy to accept and process inputs at a near-human speed.

(3) Policy or Ethics Issues. The list of ethics issues is vast; at the top of the list is that of an unmanned system making its own decisions in order to fulfill mission requirements. Another issue is determining the level of error that is tolerable in an automated system.

b. Rules of Engagement Orders/Heuristics Capability

The technologies required to achieve this capability are depicted in Figure 54. The ability to translate a specific set of Rules of Engagement into a logical construct which can be applied into the physical domain.

44 (Moore, 2012)

45 (AAI, 2011)

46 (AAI, 2011)

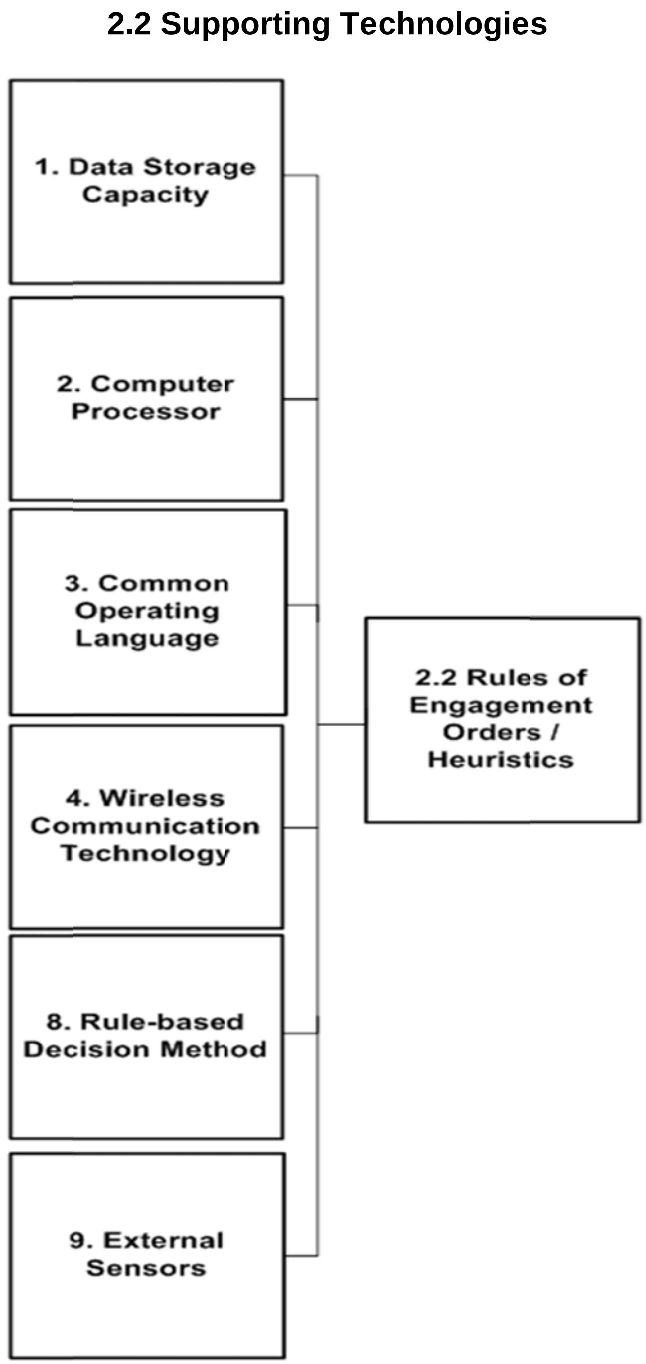

Figure 54. Rules of Engagement Orders/Heuristics

(1) Examples of Rules of Engagement Orders/Heuristics. An example which has the capability of determining courses of action with regard to ROE using semantic programing language is currently fulfilled at a low level of performance using software programs composed of countless if-then statements. ColorForth semantic programing language employs this type of function and is available and released for unlimited use.[47]

Another sematic programming language which is available to assist in fulfilling this requirement is the use of the J2EE® with the use of peripheral sensors.

A sensor available to assist in ROE is the use of the Automatic Identification System (AIS). The International Maritime Organization regulation requires that AIS provide information including the ship's identity, type, position, course, speed, navigational status and other safety-related information. Similarly, AIS automatically sends updated information to appropriately equipped shore stations, other ships and aircraft; automatically receives such information from similarly fitted ships and monitors and tracks ships.[48] The same system is employed in aircraft and has a positive identification function used by the military.

(2) Demonstration Requirements. In order to ensure this capability satisfies the TRUCC requirement a software program will need to be designed to a near-perfect level of reliability and accuracy due to the authority given to an unmanned system to provide a recommendation to the operator for weapons release authority.

(3) Policy or Ethics Issues. An ethical issue with regards to ROE is allowing a computer system to make recommendations on ROE to an operator based on the programmer's inputs and interpretation. In the case of a

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47 (Moore, 2012)

48 (International Maritime Organization, 2011)

saturated environment, the operator may choose to automatically consent to the computer's decision to use lethal force. No policy issues exist with regards to Rules of Engagement Orders/Heuristics.

c. Perform Triage Capability

The technologies required to achieve this capability are depicted in Figure 55. The ability for a network of USVs to prioritize consequences within the network of TRUCCs for correction by the operator.

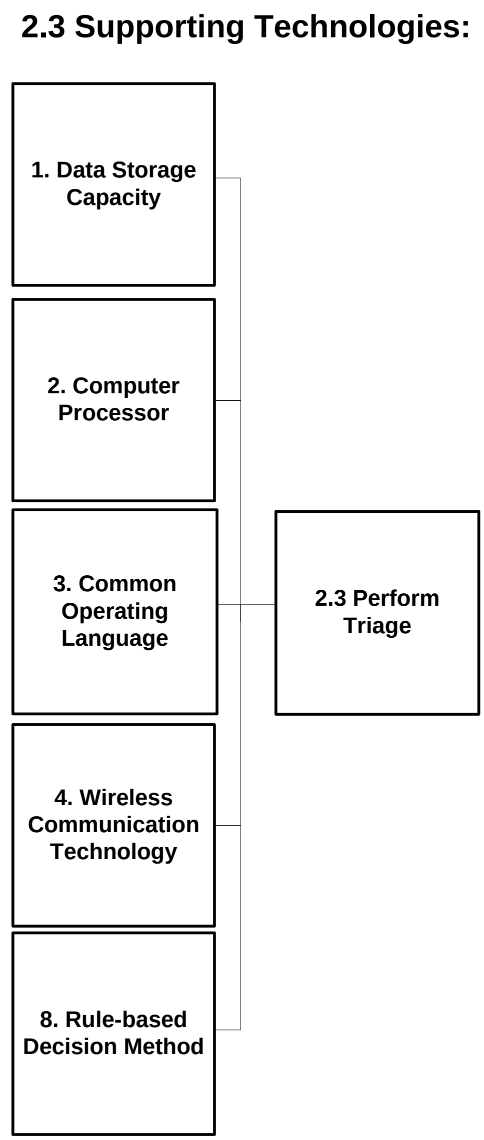

Figure 55. Perform Triage

(1) Examples of Perform Triage. An example of a capability which will perform triage with regards to the network of TRUCCs using semantic programing language is currently fulfilled at a low level of performance using software programs composed of countless if-then statements. ColorForth semantic programing language employs this type of function and is available and released for unlimited use.[49]

Another example of a system performing triage is the Mars Rover software Autonomous Exploration for Gathering Increased Science (AEGIS), which has been operating on the Mars rover Opportunity since December 2009. The software has the ability to autonomously direct Opportunity's cameras towards objects of interest.[50]

(2) Demonstration Requirements. In order to ensure this capability satisfies the TRUCC requirement a software program will need to be designed to a sufficient level of reliability and accuracy.

(3) Policy or Ethics Issues. There are no ethics or policy issues related to this capability.

d. Determine Potential Threats Capability

The technologies required to achieve this capability are depicted in Figure 56. The ability of the TRUCC to search for, detect, track and recommend engagement of a threat. Included is the ability for the TRUCC system to identify friendly/neutral contacts from enemy contacts in order to prevent noncombatant or friendly engagements.

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49 (Moore, 2012)

50 (NASA JPL, 2011)

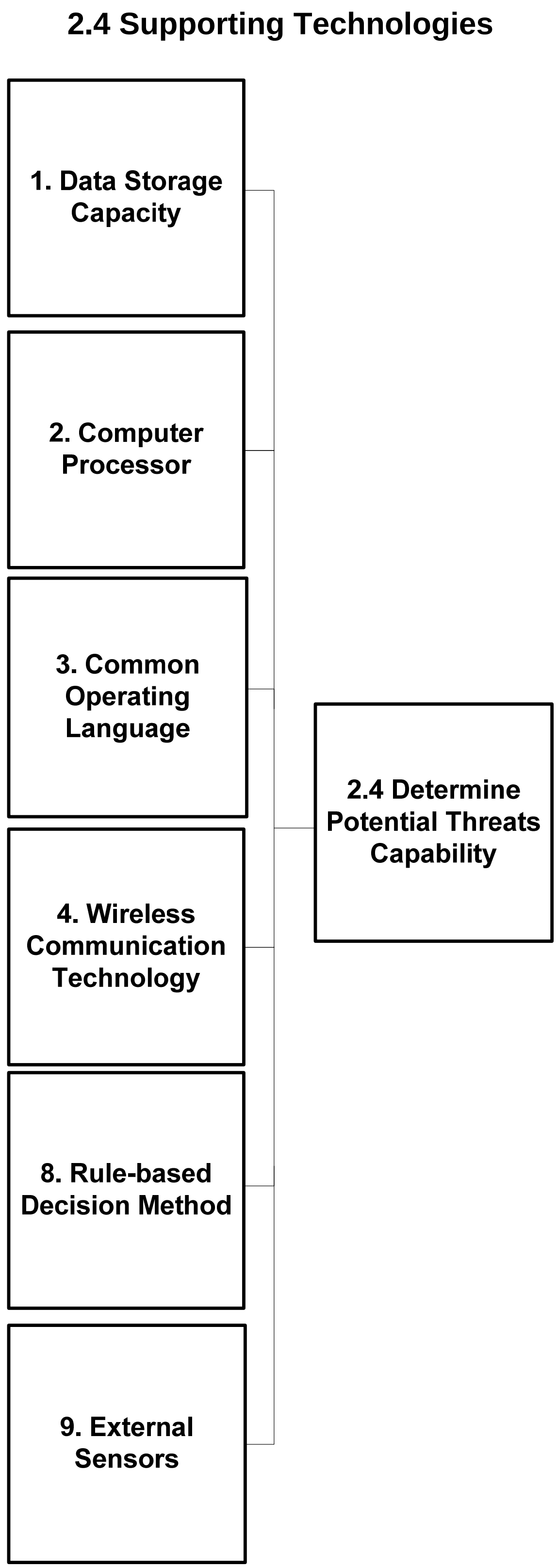

Figure 56. Determine Potential Threats Capability

(1) Examples of Determine Potential Threats. An example of a capability which will determine courses of action with regards to threats using semantic programing language is currently fulfilled at a low level of performance using software programs composed of countless if-then statements. ColorForth semantic programing language employs this type of function and is available and released for unlimited use.[51]

Another sematic programming language which is available to assist in fulfilling this requirement is the use of the J2EE® with the use of peripheral sensors, although this is a slower process than using ColorForth.

AIS can also be used for this capability. The information provided by AIS can also be used to determine if a contact is a threat as well as assist in applying the rules of engagement.

Radars, Signals Intelligence (SIGINT), Measurement and Signature Intelligence (MASINT), and optical sensors play a key role in establishing hostile contacts. Once the identity of a contact is known the computer can access the database, determine what type of threat the contact is, and relay this information to the remote operator for further direction.

(2) Demonstration Requirements. To ensure this capability fulfills the TRUCC requirement it must be thoroughly tested to ensure a high level of accuracy as well as reliability at near-human speeds.

(3) Policy or Ethics Issues. There are no ethical issues with the use of this capability as a human is still in the loop and no engagement orders are based on this capability alone. A major policy issue with this capability is the selection of the semantic programming language to be used in the network of TRUCCs.

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[51] (Moore, 2012)

e. Determine Potential Course Obstructions Capability

The technologies required to achieve this capability are depicted in Figure 57. The ability to use potential threat data including threat speed and capability in order to minimize damage to the TRUCC and network of TRUCCs.

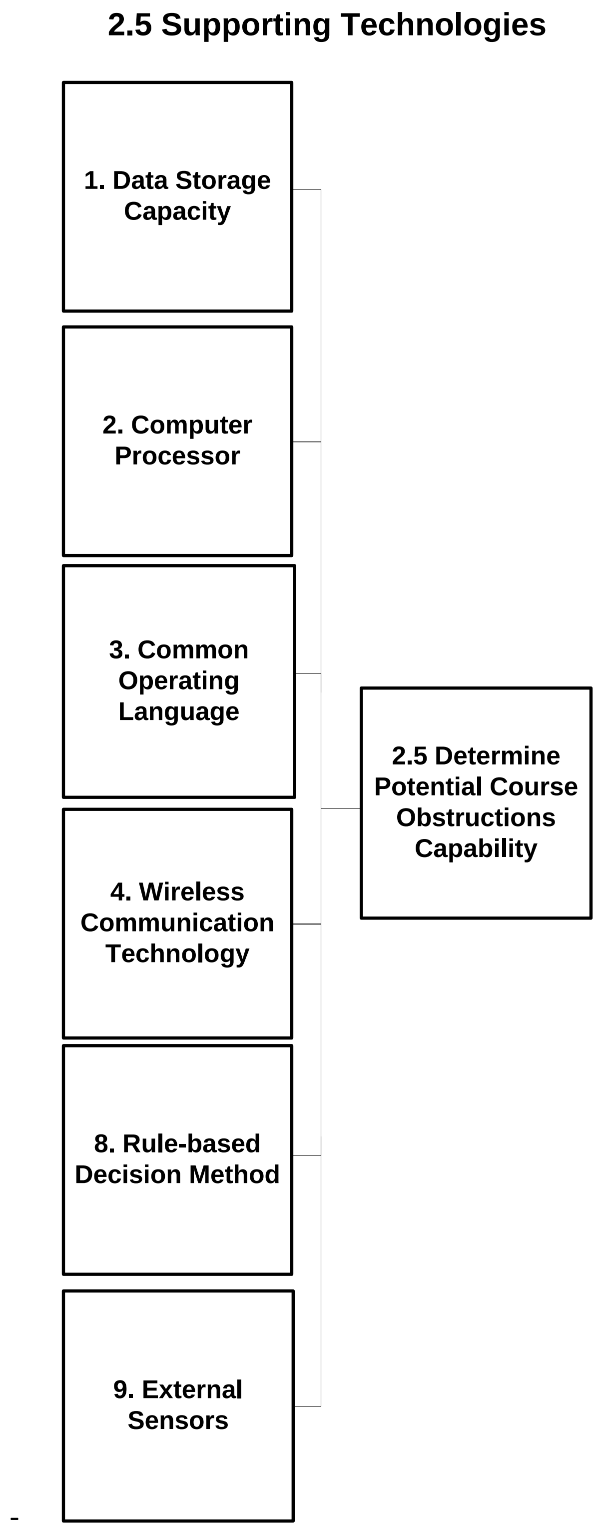

Figure 57. Determine Potential Course Obstructions Capability V 1.0

(1) Examples of Determine Potential Course Obstructions. The capability of determining courses of action with regards to threats using semantic programing language is currently fulfilled at a low level of performance using software programs composed of countless if-then statements. ColorForth semantic programing language employs this type of function and is available commercially off the shelf.[52]

Another sematic programming language which is available to assist in fulfilling this requirement is the use of the J2EE® with the use of peripheral sensors, although this is a slower process then using ColorForth.

A sensor available to assist in ROE is the use of the Automatic Identification System (AIS). The International Maritime Organization regulation requires that AIS shall provide information including the ship's identity, type, position, course, speed, navigational status and other safety-related information. Similarly, AIS shall automatically update information to appropriately equipped shore stations, other ships and aircraft; receive automatically such information from similarly fitted ships; monitoring and tracking ships.[53] The same system is employed in aircraft and has a positive identification function used by the military.

Sound Navigation and Ranging (SONAR), Radio Detection Ranging (RADAR), SIGINT, MASINT, and optical sensors as well play a key role as a sensor in detecting contacts. Once the identity of a contact is known the computer can access the database and determine the type of threat the contact is and relay this information to the remote operator for further direction or if designed take action to avoid the obstruction in the most efficient manner.

52 (Moore, 2012)

53 (International Maritime Organization, 2011)

(2) Demonstration Requirements. To ensure this capability fulfills the TRUCC requirement it must be tested to ensure a high level of accuracy as well as reliability at near-human speeds.

(3) Policy or Ethics Issues. There are no ethical issues with the use of this capability as it is merely used to avoid a threat. A major policy issue with this capability is the selection of the semantic programming language to be used in the network of TRUCCs.

f. Generate Immediate Actions List Capability

The technologies required to achieve this capability are depicted in Figure 58. The ability to generate a sequential list of actions for autonomous TRUCC action as well as operator input. This action list shall be based on TRUCC availability, system availability, threat location, and threat capability, in order to maximize the efficacy of the network of TRUCCs. The ability for the network of TRUCCs to generate the immediate action list is critical in a saturated environment.

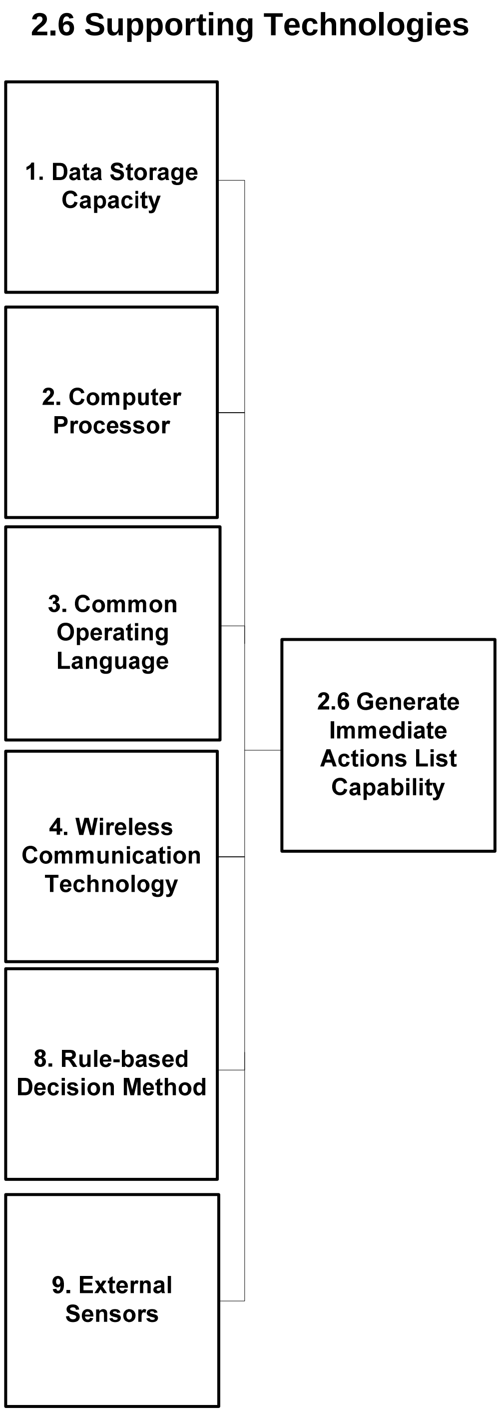

Figure 58. Generate Immediate Actions List Capability

(1) Examples of Generate Immediate Actions List. One example of a system which is able to generate its own immediate action list is called Self-Organizing Incremental Neural Network (SOINN), which is able to think, learn, and act, by itself. The Hasegawa Group from Tokyo Institute of Technology has developed this robot prototype which performs tasks quickly and accurately even when there is a slight change in the environment.[54]

Another example of a system generating an immediate actions list is the Mars Rover software AEGIS, which has been operating on the Mars rover Opportunity since December 2009. The software has the ability to autonomously direct Opportunity's cameras towards objects of interest.[55]

(2) Demonstration Requirements. To ensure this capability fulfills the TRUCC requirement it must be tested to ensure a high level of accuracy as well as reliability at near-human speeds.

(3) Policy or Ethics Issues. There are no ethical issues with the use of this capability as it is merely used to avoid a threat. A major policy issue with this capability is the selection of the semantic programming language to be used in the network of TRUCCs.

3. Autonomous Operation

The technologies required to achieve this capability are depicted in Figure 59. With this technology the TRUCCs are able to operate without a human. The TRUCCs are able to communicate to each other and other actors in the environment through wireless communications.

[54] (Hasegawa Lab, 2012)

[55] (NASA JPL, 2011)

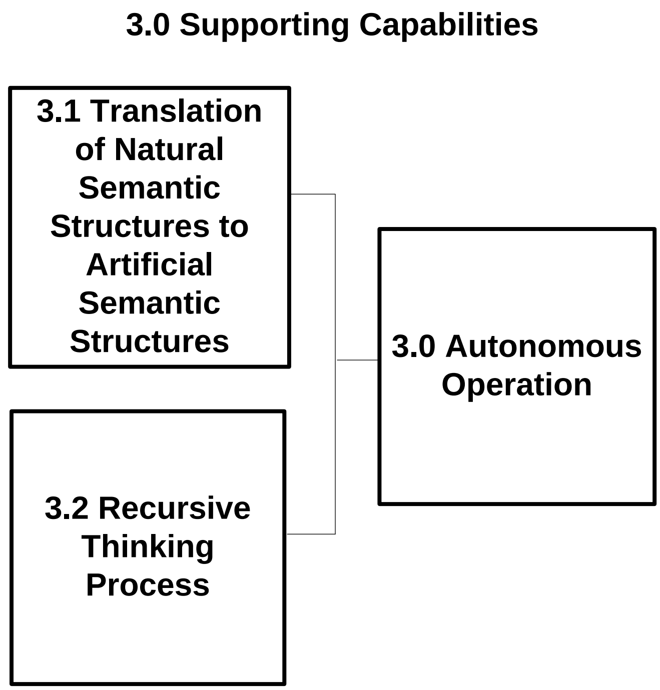

Figure 59. Autonomous Operation

H. TRANSLATION OF NATURAL SEMANTIC STRUCTURES TO ARTIFICIAL SEMANTIC STRUCTURES

The ability to translate natural to artificial semantic structures is necessary because any robot that is expected to operate autonomously has to be able to interact with the environment and humans, as well as within the context of situations. Observing and interpreting physical phenomena within that environment is an issue of sensor capability and ability to interpret that sensorial data to extract a sufficiency of information from which to provide necessary and sufficient controls to maintain an acceptable level of survivability. An example of an environment is the surface of the ocean upon which the machine floats. The physical characteristics of the environment that need to be observed are the range to other objects floating on the surface and the electromagnetic signals they are emitting. The machine has to be able to reconcile the observations with its knowledge of the situational context. Objects emitting a particular electromagnetic signal require a different type of reaction than objects not emitting a signal. For a human, the sematic representations of the objects emitting signals might be ships while those that are not emitting signals might be icebergs. The robot has to be able to understand these concepts or it will not understand how to react.

Another key issue is that the machine will have to be able to communicate and understand other agents within that environment, humans and machines. Humans generally only communicate through natural semantic expressions. If the machine is unable to "grasp" the nuances of human speech like metaphors or cannot interoperate with other machines, it will not be able to take non-standardized orders or inputs and turn them into actions. The complicating factor that inhibits this overall inoperability is coupled with the lack of ability to quickly and reliably "converse" in a meaningful manner. An example of this is "Engage the Enemy!" Until the machine has the capability to take the abstract concept of enemy and correctly apply it to the targets around itself it will always require human direction.

1. How

In order to explain the necessary steps required to achieve the capability to translate between natural and artificial semantic expressions several terms and concepts must be explained and developed. These terms are semantics, ontology, and mereology.

Semantics is a study of how people use objects and processes to represent abstract concepts. An object can be any physical object that is used to convey or receive information. For example, the word "DOG" is an object that represents a member of the canine species. Another example is the painting *The Scream* by Edvard Munch which represents the artist's view on the world.[56] A process is any combination of activities that are used to convey information or carry out the acts. The most common process used to convey information is speaking. Another example that is very familiar is making different faces to

56 (Munch)

express different emotions, like smiling to indicate happiness. The concepts represented by these objects and processes can be physical objects like a “table” or they can be non-physical such as abstract concepts like “freedom” or “oppression.” Semantics are important because it helps explain how humans interact with each other and make decisions.

Understanding how meaning is constructed is very important because it leads to the construction of the personal framework or ontology that a person uses to make decisions. Ontology is “an explicit formal specification of how to represent the objects, concepts and other entities that are assumed to exist in some area of interest and the relationships that hold among them.[57]”

All humans create and use a personal ontological structure to interact with other people and animals. The development of this ontology begins at birth and continues throughout our lives. An example of the ontological development is a baby crying. After birth a baby has no reference or framework to explain all of the sensations he or she (or it) feels like hunger, cold, hot, or pain. Babies seem to have a limited selection of choices when trying to interact with the world to effect a change in their “state.” They can sit there and suffer until the problem goes away or cry until something or someone fixes the situation.

As humans grow older they encounter and acquire more abstract concepts that are incorporated into their ontological structure. An effective method of acquiring these abstract concepts is through language. Language is not the only method, but words are the dominant objects that humans use to define and transmit ideas. This means of communication can be seen in the fact that new words are constantly being created as humans invent or discover new symbols as they interact with their environment. The ontological development of each human is, in part, governed by his or her environment and experiences.

[57] (Dictionary.com, 2008, p. 1)

Semantics are important to this process of ontological development because every language has different rules, which in turn affect how the ontological structure of that person is formed. The importance of semantics to ontological structures can most clearly be seen in how difficult it is to translate written objects from one language to another. “Sumimasen” in Japanese does not mean just mean “thank you” in English. A more accurate translation is “I have received a [debt] from you and under modern economic arrangements I can never repay you; I am sorry to be placed in such a position.”[58] The fundamental idea of indebtedness that is a main part of the Japanese speaker’s ontological structure is not present in the same form as the English speaker. Due to this there is a mismatch in the abstract concepts represented by the different objects “Sumimasen” and “Thank You.”

True translation between different languages requires that there be at least one person or agent in the situation who has all of the ontological structures present in both parties and can adjust the objects to best match the concepts present in each party’s personal ontological structure.

Development of an ontological structure is premised on the parts of ontology that relate to the totality of the topic. Across the spectrum of local and coalition needs, the ontology must affect a wider, more responsive structure to accommodate special needs in a most general sense. The example of translating one language into another language is directly applicable to this issue. Converting one language to another language, then to a third language, is a typical approach used today. However, a meta-ontology, to which all languages map, provides the most efficient translation from language to language. To that end, mereology is the study of how a part relates to the whole and how parts within a whole relate to each other. In other words, mereology is an attempt to break something down into its most basic components and define how those components are related. The concept of “mereology” was developed by

[58] (Benedict, 1967, p. 105)

Stanislaw Leśniewski. He proposed that the universe is made up of only two types of categories or parts. A possible example of this is that the Universe is composed of objects and of processes as extended through the development of subjective and objective ontology.[59] The specific definition or form of those two parts is important to semantic representations at this level of analysis, but ultimately the mereology of objects and processes must be able to explain and describe all things required for fully autonomous operations.

A standard mereology is important because only by describing the totality of items required to carry out autonomous missions, at the most fundamental and abstract level, is it possible to bridge the gap between natural semantic structures. Before the development of machines, a standardized mereology was not required because all humans are equipped with several basic ontological structures based on intrinsic common structure of our thinking. Hunger, pain, anger, and sadness are all sensations that all humans feel. This commonality helps us communicate without a common language even if most of the semantic expressions have no reciprocal match up. Translation between humans only fails when the basic design of the body is different than the norm. Trying to describe the color blue to a blind man is impossible because the blind man may not have the ontological structures related to vision because his eyes do not function correctly. Another example is trying to communicate with autistic children whose brains process incoming signals in a non-standard manner. The structures might be present but they are either inoperative or operative at a level which is less than necessary.

The problem of translation becomes even more difficult when it comes to machines because they have almost none of the same ontological structures as humans. Programming languages such as C++, RUBY, and JAVA do not represent a true translation of a human language to machine language. A human has to first translate naturally occurring semantic objects into artificial

[59] (Langford, Engineering Systems Integration: Theory Metrics, and Methods, 2012, p. 159)

semantic arguments. For example in C#, the string of objects “int VAL1 = 1;” means the object VAL1 can only be an integer and in this case it equals 1. The person writing this command knew what ontological structures the computer could use and ensured that all ambiguity was removed. The C# compiler then translates int VAL1 = 1 into the machine code commands to create a location on the hard drive where the object VAL1, its value 1, and its type integer are stored for later referencing.

The previous example is a very simple case. There are several examples of products and designs that are very good at handling a lot of the ambiguity in natural semantic expressions such as the Siri® program loaded on the iPhone 4S®. This software program interprets human speech and translates that into actions. The program is far more versatile than trying to program in C# but it is very easy to find the limits of the Siri program in being able to understand natural language. A recent and controversial example of these limits is the inability of Siri to locate rape crisis resources when asked.[60] The programmers did not add the appropriate ontological structures for the program to react to this query by the user. The problem is there are still structures in the human ontological structure that the machines ontological structure does not have.

True translation between natural and artificial structures can only be accomplished when there is a single mereology upon which an ontology is built, that includes both human and machine structures, trying to add to the ontologies of both parties until every structure is present is not sufficient if the mereology on which they are based is not the same.

In conclusion, there are three steps required for translation between natural and artificial semantic structures. The first step is to define a single mereology which all agents agree will be encountered in the environment. The second step is to expand the standard mereology into an ontology that includes

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[60] (Blue, 2011)

all structures necessary to carry out autonomous missions. The third step is to define standard set of semantic rules for describing both natural and machine semantic structures so that they can be parsed into the standardized ontology.

2. Issues for Consideration

The following are unresolved issues in the translation problem space.

- As stated in the description a standard mereology should be established in order to ensure that the natural and artificial ontologies have no areas where translation could not occur. This task will require that all parties participating in the mission environment agree to the component parts and their definitions.
- Based on the common mereology, an ontology must be designed that contains all natural and artificial structures required for the mission environment. The creation of the standard ontology, and the determination of which structures to include, presents one of the greatest challenges for the desired translation. Perhaps more importantly, however, the choice of included artificial structures directly impacts the design of the hardware supporting the translation. For example, different processors like Intel or Apple processors use different machine languages. Any designed ontology must be able compatible with the host processor's machine language in order to execute the translation program.
- The fact that the translation ontology, once complete, is linked to a particular machine language poses a limit to the interoperability of the system. For example, lack of a common chipset for the embedded systems in the mission environment may introduce a good chance of translation error. In this manner, the choice of chipset is a difficult one since performance is not the only factor. Since the end customer is the government, the choice will have several political implications that have to be considered.

- The implementation of the translation software requires that there be enough data storage and processing speed to carry out the translation at a rate at least as fast as a human, estimated at 1 x 10^{14} operations per second (roughly 1680 GHz).[61] Current technology is not able to produce the required computational speeds and storage at a size small enough to be widely used. IBM's Watson computer is one of the most advanced natural semantic processors, and reflects the current state-of-the-art in such translation tasks. Watson has "15 terabytes of RAM, 2,880 processor cores and can operate at 80 teraflops." [62] It is roughly the size of 10 refrigerators.[63] The size and complexity of Watson would make it unfeasible as a mobile combat or ISR platform. A significant jump in the miniaturization of information technology is required before natural semantic translation can be widely used in the battle space. The miniaturization may not require that the processors reach the size of the human brain (roughly 1300 g) but a significant improvement is required.

3. Demonstration Requirements

In order for a machine to prove that it has semantic translation capability sufficient to interact with all actors in the environment a Turing test is required. The machine must be compared to a control of humans who are given the same contextual information and semantic structures. If the machine has sufficient natural semantic translation capability the task list it generates must be equivalent to the task list created by the humans in the same situation.

I. RECURSIVE THINKING PROCESS

True autonomy requires that the autonomous agent is able to use its body of knowledge to accomplish a task using recursive and iterative thinking

61 (Moravec, 1997, p. 3)

62 (Gustin, 2011, p. 1)

63 (Gustin, 2011, p. 2)

processes within a schema or model of the contextual environment. Current rule-based programming techniques are able to apply a large set of problem-solving techniques using trial and error. This process is iterative. If the first technique fails the second technique is applied. The machine applies each of the techniques available to the problem in sequence. The problem with this method is that if all of the different techniques the machine is able to use do not work, then the machine cannot proceed with its assigned task. At this point, a recursive process is required in order to generate a new set of problem solving techniques to be applied, not just permutations and modification of failed problem methods.

Humans are able to apply recursive thinking to bridge the gap between a set of failed problem solving techniques to another possible set of problem solving techniques. An example of the use of recursive thinking can be seen in the recent search for the treasure ship *Soleil D'Orient*.[64] The searchers used recursive thinking to apply their knowledge of the ship's course, environmental conditions, and other factors to create an area that should be searched. The searchers used an iterative method to effectively search the proposed area using trial and error. At the end of the iterative search process the treasure was not located in the search area. The searchers at this point turned to a recursive process based on the schema or model of the situation to create a new search area. If the ship was not in the proposed search area then it must be somewhere else. Based on the model of the ship, the environmental conditions, and the knowledge where the ship was presumed not to be located the searchers decided to search on land rather than the ocean bottom. Given a new search area the iterative process was applied again which eventually led to the discovery of the ship's location.[65]

[64] (Treasure Shipwrecks Around the World)

[65] (Langford, Discussions on Recursive Thinking, 2012)

The difficulty with recursive processes is that they are not based on rules. In the treasure-hunting example, the decision to search on land seems logical in hindsight, although several experts in ship driving had indicated that it was extremely risky and therefore untenable for the captain of the *Soleil D'Orient* to have beached his ship. In order to arrive at the correct search method, the searchers were required to ignore credible data with no logical justifications. In this manner, humans are able to generate new courses of action without a logical set of inputs.

The recursive process is not perfect and does not always lead to a solution. If the agent using a recursive process does not have all the knowledge required, it may never reach a solution to the problem. The difference between a human and a machine is that with recursive processes the human is able to continue to try new problem solving methods without inputs from other agents. Truly autonomous machines must be able to execute some level of recursive thinking in order to eliminate the human operator completely.

1. HOW

The main barrier to achieving recursive thinking is that currently the methods or mechanisms by which humans conduct recursive thinking is unknown. There are several open questions in terms of how humans actually conduct this process, including the one of how the brain structure is linked to its function or performance. Neurobiologists have been able to identify the specific chemical and physical structures comprising a synapse, but have not been able to conclusively identify how those structures relate to learning.[66]

There are two bodies of thought on the question of how the brain operates. The first is the connectionist idea that problem solving is based on how the synapses are connected. As more connections are added the better the problem solving capability. In this theory of brain function there are no separate

[66] (Douglas & Sejnowski, 2007, p. 13)

controllers for higher brain function.[67] Connectionist theory has been popular because two of the knowledge application techniques derived from it, adaptive resonance theory and back propagation, have accounted for most of the gains associated with machine learning. The problem with these techniques is that a human conducts the metacognition process for the machine by determining the values of various input variables. The connectionist view is also limited because it posits that there must always be a feedback signal necessary for learning to occur. The requirement of some form of feedback is not part of human metacognition and knowledge application since humans are more than able to act without any feedback from their actions. The lack of feedback is shown in the proximate causal response most humans exhibit.[68] A human uses their sensory organs to take in information and use it to anticipate the environment around them.[69]

The second body of thought is the controller theory of the brain. The controller theory argues that there are several executive controllers in the brain that control and regulate other parts of the brain.[70] The controller body of theory requires that there is some type of control structure like a hierarchy of executive and subservient subsystems. The Controller Theory has several weaknesses. Research has indicated that the brain controllers are most likely organized in heterarchical architecture rather than a hierarchical architecture. The different controlling functions have multiple different types of connections between them so that depending on the function being enacted the executive controller can change; there is no single top-down structure that works for all operations as in a hierarchy. In other words, the controller in charge changes depending on the operation the brain is trying to implement. The problem is that researchers are

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[67] (Roy, 2008, p. 1)

[68] (Langford, Engineering Systems Integration: Theory Metrics, and Methods, 2012)

[69] (Langford, A Theory of Systems Engineering Integration, 2012)

[70] (Roy, 2008, p. 2)

not completely sure how the brain interacts during different operations. Many different actions have been identified, but there is no comprehensive theory to explain all interactions that occur in the brain for learning to occur.

The actual neural architecture of the brain is probably something between the connectionist and controller theory bodies of thought. Animal and human learning processes though, are the only working examples of autonomous learning existing on the planet.

Another barrier to autonomous learning is computer hardware limits. There is no consensus to calculate and measure the computational abilities of the human brain, but one approximation comparing the size of the retina to the brain puts the value at 100 million MIPS (millions of instructions per second) or 1 x 10^{14} operations per second. Based on this value there are several computers that have surpassed this limit with the Chinese Tianhe-1A clocking in at 2.5 petaflops or 2.5 x 10^{15} operations per second.[71] The problem with these computers is that even with today's technology they are the size of small buildings. The concept of intelligent machines requires that they can interact with our environment in a manner similar to humans. By implication, this means that those machines need to be similar in size to humans. The average human brain is roughly 1300g.[72] A computer the size of a building clearly does not meet this criterion.

2. Issues for Consideration

The following are unresolved issues in the recursive thinking process problem space.

- What level of metacognition is required for machines to operate autonomously? Humans are not infallible and occasionally make mistakes. The expectation of most policy makers is that machines must

71 (Marshall, 2011, p. 1)

72 (Washington University, 2011, p. 1)

perform nearly perfectly in order for them to operate autonomously. That expectation does not apply in most real world situations, especially in the uncertainty of combat situations, and even more especially in cases where such objective metrics of a “right answer” are unavailable or unreasonable.

- Who is responsible for human-like machines? The legal implications of the liabilities created by employment of these machines must be addressed. A possible precedent may exist in the treatment and law regarding pets, such as dogs. Many states have instituted laws where the owner is automatically liable for any injuries caused by a dog.[73] Other states have instituted a rule that looks at the prior history of a dog to determine if the owner should be liable. Some of the criteria examined in these cases is whether the dog has been trained to fight, or if the dog actively threatens people.[74] It is important to determine the specific rules regarding autonomous machine before they are deployed in an environment where they could cause injury to humans.
- What level of recursive thinking is required for TRUCCs? Not all humans have the same knowledge, nor do they have the same ability to conduct recursive thinking to generate new problem solving methods. Does the machine merely require the abilities of an average ten-year-old or must it possess the abilities of a genius thinker to satisfy the preconditions of recursive thinking? Given the current state-of-the-art and our nascent understanding of how to implement recursive thinking capabilities in machines, it is difficult to estimate the cost for development of increased recursive thinking ability in future machines.

[73] (Randolph)

[74] (Randolph)

3. Demonstration Requirements

The machine must be able to pass a classical Turing test. A Turing test is an experiment that is designed to prove the presence of "mind, thought, or intelligence in an entity."[75] The machine, when given the same knowledge and tasks, must be able to continually cycle through the recursive and iterative processes without human assistance. Each time through the cycle, the machine must devise and execute new problem solving methodologies to reach a previously undiscovered objective in the same manner as a human.

4. Recommendations

Based on the analysis of current technologies and capabilities there are several recommendations.

- Increase investment and continued development of detailed rule sets for capabilities 2.1 through 2.6. The logic and low-level autonomy represented by these capabilities are still in their technological infancy. Improvements in these capabilities will increase the number of UXVs that can be effectively controlled by a single human operator. The increase will, in turn, raise the level at which saturation will occur in terms of network externality. The examples mentioned in each section are good starting points for further research.
- Increase investment into research projects focused on the development of more effective natural to artificial semantic translation to support capability 3.1. The developers of the Semantic Web have made great strides in establishing a standard mereology and ontology required for true translation.[76]

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[75] (Oppy & Dowe, 2011)

[76] (Mao, Peng, & Spring, 2010, p. 2)

- Increase investment into research projects highlighting the insights afforded by cognitive neuroscience and deeper understanding of the human brain in support of capability 3.2. There are several ongoing projects, including, for example, the projects and ideas mentioned in the 2007 Future Challenges for the Science and Engineering of Learning July 23-25 Final Workshop Report.[77]
- Begin the development of legal test cases to explore the ramifications of autonomous machines, specifically spotlighting the issues of foreseeable harm and tort liability. An illustrative legal thought experiment would be to identify the liable party if the Google autonomous car crashes into a fire hydrant. Would the Google company itself be held responsible, or perhaps the team of programmers who implemented the faulty logic would be faulted? Of relevance to military autonomous systems, if an autonomous machine kills a civilian, should just the offending machine be destroyed, if at all, or should all machines loaded with the same decision making software be recalled and/or de-activated?
- Continue pursuit of an open architecture standard for connecting dissimilar machines. Though open architecture will not help in achieving full autonomy, it will help near-term integration of developing foundational systems. As discussed earlier in the translation discussion, a meta-ontology structure can be useful for facilitating this integration. The Global Information Network Architecture (GINA) programming structure is an example of a very successful meta-ontology structure currently in use today.[78]

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77 (Douglas & Sejnowski, 2007)

78 (Tudor, Tinsely, & Busalacchi, p. 2)

XII. MISSION EFFECTIVENESS TECHNICAL COMPENDIUM

A. PURPOSE

The Mission Effectiveness Model has two main purposes. The first purpose was to determine which physical characteristics of the TRUCC had the most affect upon mission success. The second purpose was to act as a tool to determine the effectiveness of proposed TRUCC designs created by the Mission Vehicle Model.

B. MODEL 1.0 FACTOR EXPLORATION DESIGN

1. TRUCC Factor Selection

The TRUCC factor selection started first with the creation of a Design Reference Mission (DRM) in which to place the TRUCCs and the attacking force. The DRM was created so that the TRUCCs act as a defensive force for a HVU against a swarm of incoming enemies of varying capabilities. Using the experience of the group and the DRM a causal diagram (Figure 60) was developed to show the possible interactions of agent capabilities. The red and blue factors listed in the diagram are the independent characteristics of the TRUCC and the attackers in the DRM. All of these factors combine to determine the values of the secondary factors in green. These factors combined with additional independent factors to determine the tertiary factors (shown in black) where the Measures of Effectiveness for the system are determined. A more detailed discussion of MOE and MOPs follows later in the report.

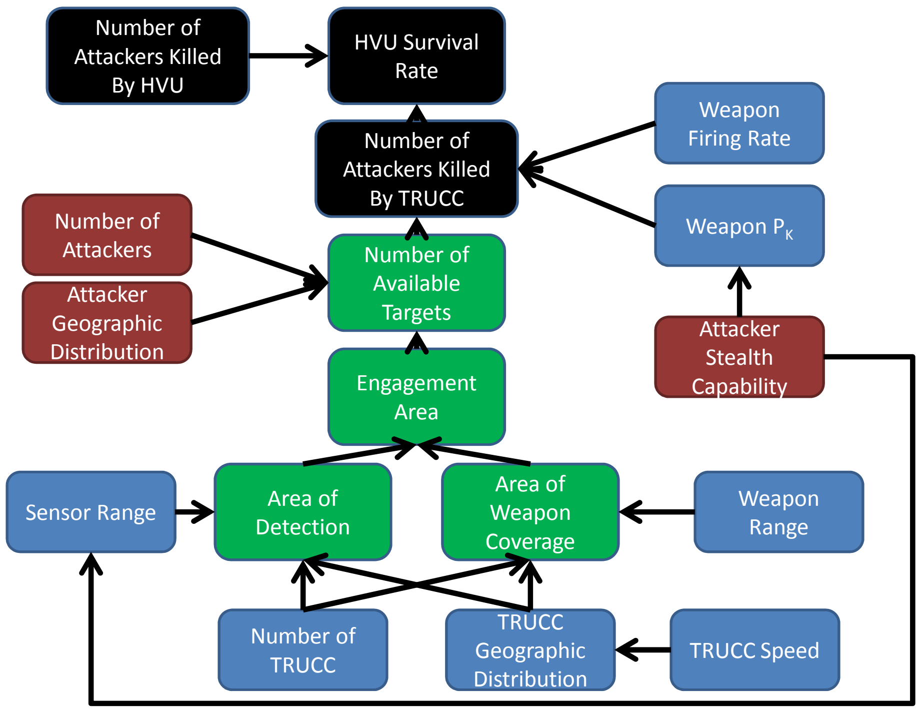

Figure 60. Causal Diagram

After examining the causal diagram and comparing it to the capabilities of the MANA software, seven parameters were investigated:

1. Sensor Detection Range
2. Number of TRUCCs
3. TRUCC Speed
4. Weapon Range
5. Weapon PK
6. Weapon Firing Rate
7. Sensor Detection Probability

TRUCC geographic distribution was not selected as a factor for investigation because any attempts at optimizing system performance based on positioning is reflective of tactics, rather than system capability. In order to remove the geographic distribution of the TRUCCs as a factor the TRUCCs always begin each simulation in a screening formation around the high value unit at roughly 2000 meters. It is assumed that the defending force has no prior knowledge of the attacking force so there is no positioning along a specific threat axis. This basic screening formation serves as a plausible tactical employment regime to baseline TRUCC performance. The effect of attacker stealth capability was accounted for by adjusting the detection rate of the TRUCCs sensor so that even if the attacker is within sensor range, it was not immediately available for targeting.

Each of these factors was given upper and lower bounds in order to facilitate a screening experiment. The factors and their values against a particular attacker type are summarized in Table 21. It should be noted that the sensor detection range, weapon range, and weapon firing rate are different against the FAC/FIAC threat because it is assumed that that type threat cannot be engaged with a missile system and a gun type system must be used.

Table 21. TRUCC Factor Values

	Scenarios	**ASCM**		**LSF**		**FAC/FIAC**	
No.	**Blue USV**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
1	Number of TRUCCs	20	60	20	60	20	60
2	Speed of TRUCC (m/s)	10	50	10	50	10	50
3	Sensor Detection Range (m)	5000	15000	5000	15000	200	3000
4	Sensor Detect Probability	0.5	0.9	0.5	0.9	0.5	0.9
5	Weapon Range (m)	5000	15000	5000	15000	200	2500
6	Weapon Pk	0.25	0.75	0.25	0.75	0.05	0.1
7	Weapon Firing Rate (sec)	10.02	100.2	10.02	100.2	1	2

2. Attacker Capabilities

The attacker capabilities were chosen based on several assumptions. The first assumption was that the attacking force was disposable and that preservation of those assets was not a high priority. The second assumption was that the attackers were only equipped to kill the HVU and would not target the TRUCCs. The attackers, though, were advanced enough that they were equipped with sensors capable of detecting the TRUCCs and evading them.

Per the DRM, the different types of attacker are anti-ship cruise missiles, low slow flyers, and Fast Attack Craft / Fast Inshore Attack Craft. ASCM and LSFs can be engaged with missiles but FAC/FIAC cannot. The capabilities of each attacker are listed in Table 22.

The LSF and the FAC/FIAC attackers can exhibit two distinct types of behavior; smart or dumb. Dumb attackers do not try to avoid the TRUCCs, even if they detect them. This behavior simulates attackers that drive towards the HVU regardless of defender tactics or capabilities. Smart attackers attempt to avoid the TRUCCs while still trying to reach the HVU. These different behaviors represent two possible attacking system behaviors. There is a virtually infinite variety of tactics, geographic and temporal distributions that could be utilized by swarm attacks. These two behaviors are an attempt to constrain the problem to a workable variable space. The time constraints of the project prevented the use of a greater number of threat systems combinations.

Of note, missiles always exhibit dumb behavior. It is assumed that missile evasive maneuvering in response to defender tactics is limited by physics, material strength of the airframe, and ASCM onboard processing and sensing capabilities. In order to execute smart behavior, an ASCM would require onboard sensors and processing necessary to generate evasive maneuvering of a magnitude necessary to influence defensive weapon performance. This is deemed unlikely, given the limits of high performance missile design constraints. The impact of pre-programmed terminal maneuvering schemes is effectively modeled through variation of the TRUCC weapon Pk.

The characteristics of threat systems were derived from the performance of high-technology fielded systems of today. The underlying assumption was that the difficult-to-produce, high-technology fielded systems of today will be highly proliferated in the future. These threat systems will likely be used for swarm attacks over the 40–50 year time span of this study. This study made no attempt to conduct analysis on disruptive weapons technologies of the future. Those disruptive technologies will undoubtedly influence the battlespace;

however, they are less likely to proliferate in the time scope of this project. Anticipating and planning defensive systems for possible future disruptive weapons technologies is beyond the scope of this study. Attacker characteristics are listed in Table 22.

Table 22. Attacker Characteristics

Threat Characteristics	ASCM	LSF	FAC/FIAC
Number of Threats	60	60	60
Speed of Threat (m/s)	1012	111	20.58
Sensor Detection Range (m)	15000	15000	15000
Sensor Detect Probability	1	1	1
Weapon Range (m)	200	200	200
Weapon P_K	1	1	1
Weapon Firing Rate (sec)	1	1	1

3. Asymptotic Variance

Before developing the specifics of the experimental design for the entire factor space, a separate experiment was conducted to determine the asymptotic variance of the scenario. Due to the complexity of the scenarios, it was important to conduct enough trials for each data point to ensure that the results are not skewed by extreme results. In order to accomplish this, a single scenario was selected for examination. 150 trials were conducted to calculate the mean and variance of the casualties. Table 23 summarizes the results of this experiment. Based on the results, at least 100 trials are required to ensure a constant variance. It is assumed that the different data points or scenarios are sufficiently stable that 100 trials will be sufficient for all cases.

Table 23. Asymptotic Variance

# Trials	Mean Red Casualty	Red Casualty Variance
5	10.8	6.2
10	13.5	22.5
15	13.3	21.6
20	13.0	12.7
25	13.1	15.8
30	12.4	8.1
35	13.3	17.8
40	12.5	23.4
45	12.6	19.5
50	12.2	12.6
55	12.2	8.2
60	12.2	12.7
65	13.0	9.7
70	13.0	11.0
80	12.4	10.1
90	12.2	9.1
100	12.6	12.0
110	12.7	12.1
120	12.6	11.1
130	13.1	13.5
140	12.4	12.7
150	12.7	11.9

4. Design of Experiment

The design of experiments had to be repeated a minimum of five times for the different possible attacker configurations (ie Smart LSF or Dumb FAC/FIAC, etc). In order to ensure enough degrees of freedom that the second-order interactions could be examined, a half factorial was design was selected, creating 64 scenarios. An additional ten center points were added for a basic design of 74 different scenarios. In order to ensure that the variability of each scenario was represented, the basic design was repeated eleven times for a total of 814 scenarios for all five attacker configurations.

5. Measure of Effectiveness Selection

The MOE for the DRM in question is the probability of survival of the HVU. The primary supporting Measures of Performance are the number of attackers killed by the HVU and TRUCCs, respectively. This assumes that the threat systems have an effective Pk of 1; if they evade the HVU or TRUCC defenses, that the HVU will suffer a mission kill. Each HVU has its own defensive capabilities; those range from robust layered defensive systems (such as DDGs) to no defensive equipment (such as Military Sealift Command vessels). This wide range of defensive capabilities makes it impractical to derive DRM MOE directly. The number of attackers killed by the TRUCC fleet is the measure of performance investigated in the model. By assuming a defenseless HVU, the analysis will focus on TRUCC parameters, and avoid interdependencies caused by interactions with HVU targeting systems. Operational level tactical considerations of cooperative engagement between manned and unmanned systems are left to further development. As such, the primary analysis metric for Mission Effectiveness is the MOP "number of attackers killed by TRUCCs."

C. MODEL 1.0 FACTOR EXPLORATION RESULTS

1. Analysis Approach

Pareto charts were used in the JMP® software to establish an importance ranking among the explanatory variables. This required a multiple variable regression prediction model. A variable's rank of importance does not necessarily secure its place in the prediction model; selection to the model depends on P-values and R-square marginal benefit. The most important factors for each scenario are summarized in Table 24.

Table 24. Factor Summary

Scenario	Missile Dumb	UAV Dumb	UAV Smart	USV Dumb	USV Smart
Factor 1	Weapon Firing Rate	Weapon Firing Rate	Weapon Firing Rate	Number of TRUCCs	Sensor Range * Weapon Range
Factor 2	Weapon Pk	Number of TRUCCs	Weapon Pk	Sensor Range * Weapon Range	Weapon Range
Factor 3	Number of TRUCCs	Weapon Pk	Number of TRUCCs	Weapon Range	Number of TRUCCs
Factor 4	Sensor Range	Sensor Range	Weapon Pk * Weapon Firing Rate	Weapon Pk	Weapon Pk
Factor 5	Weapon Pk * Weapon Firing Rate	Sensor Range * Weapon Range	Number of TRUCCs * Weapon Firing Rate	Weapon Firing Rate	Weapon Firing Rate

2. Prediction Model Analysis

Multiple variable linear regression models were fitted to create predictions of the number of reds killed by blue defenders in each scenario. The stepwise regression process performed by the JMP® software enters a single variable in each step according to its R-square value. The variable with the highest marginal addition to the adjusted R-square value is selected as the next explanatory variable to enter the regression model. As the number of variables used increases, the marginal "benefit" to the R-square value diminishes. Due to this fact a boundary of 1.5% was established for the added marginal benefit. Once the margin was smaller, no more variables were selected for the model. In addition a boundary of 0.25 was set for the P-values of each variable entering the model. The analysis of input variables into the model included up to second-order products of independent variables. The prediction equations for each scenario in the half factorial experiments can be found under its corresponding section in Appendix B.

D. MODEL 1.0 PROTOTYPE EVALUATION DESIGN

In addition to the Model 1.0 Factor Exploration experiment, a second experiment was designed to evaluate the Small, Medium, and Large TRUCC designs created by the Mission Vehicle ship synthesis process. The experiment differed from the factor exploration experiment because most of the factors, such as weapon ranges, sensor ranges, and TRUCC speed, were determined by the type of TRUCC being evaluated. The specific design factors for the Small, Medium, and Large TRUCCs are summarized in Table 5. The goal of the prototype evaluation model was to analyze the performance of the TRUCC network defense as the number of TRUCCs increased versus the same attacker configurations used in the Factor Exploration Experiment. The design of experiments created a series of scenarios where configuration of the TRUCC remained constant as the number increased.

It should be noted that the software limits of MANA prevented a complete evaluation of the Medium and Large TRUCC designs. MANA only allows a maximum number of six weapons to be allocated to any agent. This limit is below the proposed design for 7 and 18 small caliber weapons on Medium and Large TRUCCs respectively. In order to complete the experiment, the number of weapons for each design was modeled as indicated in Table 25. Since the maximum firepower was not available for these configurations, the experimental results for these configurations should be considered conservative. It was also assumed that the Large TRUCC would have a performance at least as good as the Medium TRUCC against the Smart and Dumb FAC/FIAC threat since the large design has more available gun systems than the medium design.

Table 25. Small, Medium, and Large TRUCC Specifications

TRUCC DESIGN	Small	Medium	Large
Design Specifications			
Speed of Blue (m/s)	20.58	20.58	20.58
Sensor Detection Range (m)	16400	22700	55300
Sensor Detect Probability	0.5	0.5	0.5
Number of Missile Launchers	0	0	1
Missile Range (m)	20000	20000	20000
Missile Pk	0.7	0.7	0.7
Missile Firing Rate (cycle time sec)	1	1	2
Number of Medium Caliber Machine Gun	0	1	3
Medium Caliber Machine Gun Range (m)	2700	2700	2700
Medium Caliber Machine Gun Pk (per round)	0.0001	0.0001	0.0001
Medium Caliber Machine Gun Firing Rate (rounds/minute)	300	300	300
Number of Small Caliber Machine Guns	3	5	3
Small Caliber Machine Gun Range (m)	2000	2000	2000
Small Caliber Machine Gun Pk (per round)	0.0001	0.0001	0.0001
Small Caliber Machine Gun Firing Rate (rounds/minute)	550	550	550

The starting number of number of TRUCCs to be evaluated was increased until the point at which all 60 of the attackers were killed all 100 repetitions of the scenario. In order to achieve the stated MOP while defending an HVU with no defensive capability, this is the minimum number of defensive systems would ensure survival.

E. MODEL 1.0 PROTOTYPE DESIGN EVALUATION RESULTS

1. Dumb Missile Results

The Small, Medium, and Large TRUCC design performance against the dumb ASCM threat is summarized in Table 26.

Table 26. Small, Medium and Large vs. Dumb ASCM

DUMB ASCM							
	TRUCC DESIGN	SMALL		MEDIUM		LARGE	
# UNITS	Force Ratio (B/R)	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV
1	0.02	5.53	2.79	8.30	3.96	29.05	4.25
2	0.03	6.03	3.20	10.54	4.66	54.41	4.62
3	0.05	7.58	3.36	14.92	5.89	60.00	0.00
4	0.07	9.81	4.41	19.36	7.42	60.00	0.00
5	0.08	12.03	5.29	25.77	9.20	60.00	0.00
6	0.10	15.70	6.86	33.71	11.00	60.00	0.00
7	0.12	16.18	7.13	41.32	9.97	60.00	0.00
8	0.13	17.98	6.71	47.95	11.23	60.00	0.00
9	0.15	21.15	7.70	53.45	10.60	60.00	0.00
10	0.17	24.34	8.89	56.84	7.31	60.00	0.00
11	0.18	25.13	10.00	58.74	5.40	60.00	0.00
12	0.20	31.26	12.72	59.95	0.50	60.00	0.00
13	0.22	35.01	12.01	59.89	1.10	60.00	0.00
14	0.23	38.26	11.33	60.00	0.00	60.00	0.00
15	0.25	43.04	12.91	60.00	0.00	60.00	0.00
16	0.27	45.64	12.78	60.00	0.00	60.00	0.00
17	0.28	49.11	13.43	60.00	0.00	60.00	0.00
18	0.30	50.59	12.26	60.00	0.00	60.00	0.00
19	0.32	53.03	10.24	60.00	0.00	60.00	0.00
20	0.33	53.94	11.19	60.00	0.00	60.00	0.00
21	0.35	57.51	6.81	60.00	0.00	60.00	0.00
22	0.37	57.80	6.92	60.00	0.00	60.00	0.00
23	0.38	58.08	6.02	60.00	0.00	60.00	0.00
24	0.40	58.31	6.10	60.00	0.00	60.00	0.00
25	0.42	59.24	3.45	60.00	0.00	60.00	0.00
26	0.43	59.59	2.75	60.00	0.00	60.00	0.00
27	0.45	59.78	1.70	60.00	0.00	60.00	0.00
28	0.47	59.72	2.80	60.00	0.00	60.00	0.00
29	0.48	59.97	0.30	60.00	0.00	60.00	0.00
30	0.50	59.85	1.50	60.00	0.00	60.00	0.00
31	0.52	59.91	0.90	60.00	0.00	60.00	0.00
32	0.53	60.00	0.00	60.00	0.00	60.00	0.00

2. Smart LSF Results

The Small, Medium, and Large TRUCC design performance against the smart LSF threat is summarized in Table 27.

Table 27. Small, Medium, and Large VS Smart LSF

SMART LSF							
	TRUCC DESIGN	SMALL		MEDIUM		LARGE	
# UNITS	Force Ratio (B/R)	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV
1	0.02	4.85	2.02	3.18	1.99	24.78	2.73
2	0.03	17.91	8.48	18.93	15.54	47.05	4.41
3	0.05	16.84	4.61	21.72	15.00	60.00	0.00
4	0.07	22.65	6.31	29.84	16.92	60.00	0.00
5	0.08	28.03	8.60	42.76	18.22	60.00	0.00
6	0.10	41.42	11.79	54.48	12.71	60.00	0.00
7	0.12	52.88	10.74	59.05	4.43	60.00	0.00
8	0.13	57.83	5.09	59.48	3.46	60.00	0.00
9	0.15	59.07	3.76	59.60	3.02	60.00	0.00
10	0.17	59.91	0.61	59.74	2.60	60.00	0.00
11	0.18	59.90	1.00	59.73	2.70	60.00	0.00
12	0.20	59.97	0.30	60.00	0.00	60.00	0.00
13	0.22	60.00	0.00	60.00	0.00	60.00	0.00
14	0.23	60.00	0.00	60.00	0.00	60.00	0.00
15	0.25	60.00	0.00	60.00	0.00	60.00	0.00

3. Dumb LSF Results

The Small, Medium, and Large TRUCC design performance against the dumb LSF threat is summarized in Table 28.

Table 28. Small, Medium, and Large VS Dumb LSF

DUMB LSF							
	TRUCC DESIGN	SMALL		MEDIUM		LARGE	
# UNITS	Force Ratio (B/R)	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV
1	0.02	4.70	1.91	11.53	3.64	31.47	4.54
2	0.03	7.81	2.60	19.24	5.67	59.04	1.89
3	0.05	10.17	3.73	30.32	8.74	60.00	0.00
4	0.07	15.24	5.82	45.52	11.01	60.00	0.00
5	0.08	20.91	7.44	57.83	5.33	60.00	0.00
6	0.10	25.41	8.98	58.74	5.40	60.00	0.00
7	0.12	33.67	11.75	60.00	0.00	60.00	0.00
8	0.13	42.98	13.60	60.00	0.00	60.00	0.00
9	0.15	48.95	11.85	60.00	0.00	60.00	0.00
10	0.17	53.41	10.37	60.00	0.00	60.00	0.00
11	0.18	56.75	7.00	60.00	0.00	60.00	0.00
12	0.20	59.43	2.88	60.00	0.00	60.00	0.00
13	0.22	59.76	1.71	60.00	0.00	60.00	0.00
14	0.23	59.70	2.24	60.00	0.00	60.00	0.00
15	0.25	60.00	0.00	60.00	0.00	60.00	0.00
16	0.27	60.00	0.00	60.00	0.00	60.00	0.00
17	0.28	60.00	0.00	60.00	0.00	60.00	0.00

4. Smart FAC/FIAC Results

The Small and Medium TRUCC design performance against the smart FAC/FIAC threat is summarized in Table 29.

Table 29. Small and Medium VS Smart FAC/FIAC

SMART FAC/FIAC					
	TRUCC DESIGN	SMALL		MEDIUM	
# UNITS	Force Ratio (B/R)	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV
1	0.02	15.87	4.23	22.64	12.73
2	0.03	30.81	5.40	55.90	4.59
3	0.05	44.96	5.98	60.00	0.00
4	0.07	56.91	4.24	60.00	0.00
5	0.08	59.93	0.53	60.00	0.00
6	0.10	60.00	0.00	60.00	0.00
7	0.12	60.00	0.00	60.00	0.00
8	0.13	60.00	0.00	60.00	0.00
9	0.15	60.00	0.00	60.00	0.00
10	0.17	60.00	0.00	60.00	0.00

5. Dumb FAC/FIAC Results

The Small and Medium TRUCC design performance against the dumb FAC/FIAC threat is summarized in Table 30.

Table 30. Small and Medium VS Dumb FAC/FIAC

DUMB FAC/FIAC					
	TRUCC DESIGN	SMALL		MEDIUM	
# UNITS	Force Ratio (B/R)	AVERAGE # RED KILLED	STDEV	AVERAGE # RED KILLED	STDEV
1	0.02	15.73	4.06	27.52	4.13
2	0.03	30.87	5.43	54.99	4.89
3	0.05	45.25	6.36	60.00	0.00
4	0.07	58.14	4.10	60.00	0.00
5	0.08	60.00	0.00	60.00	0.00
6	0.10	60.00	0.00	60.00	0.00
7	0.12	60.00	0.00	60.00	0.00
8	0.13	60.00	0.00	60.00	0.00
9	0.15	60.00	0.00	60.00	0.00
10	0.17	60.00	0.00	60.00	0.00

6. Prototype Design Evaluation Summary

The number of Small, Medium, and Large TRUCCs required to ensure 100% red casualties 100% of the time is summarized in Table 31.

Table 31. Summary of Design Evaluations

Required Numbers for 100% Red Casualties			
THREAT	SMALL	MEDIUM	LARGE
DUMB ASCM	32	14	3
SMART LSF	13	12	3
DUMB LSF	15	7	3
SMART FAC/FIAC	6	3	3
DUMB FAC/FIAC	6	3	3

The Large design, which has the longest weapon range and highest probability of kill is the most effective against both the missile and LSF threats. The Small and Medium TRUCCs perform almost equally against the Smart LSF threats; however, there is a major difference between the number of Medium TRUCCs and Small TRUCCs for the Dumb LSF threat. In this scenario, the medium-caliber weapon of the Medium TRUCC is able to engage enough incoming Dumb LSFs that they do not overwhelm point defenses. Interestingly, Small TRUCCs are overwhelmed by the Dumb LSF threat. The near-simultaneous arrival of Dumb LSFs, coupled with the short range, small-caliber weapons combined to generate a more stressing scenario than the Smart LSF threat. Smart LSFs circle around the Small TRUCC defensive formation, and attack the HVU in small groups, or as singles, when opportunities present themselves.

F. MODEL 1.1 DESIGN

1. Importance of Delay

A second design was created in order to explore the effects of a delay in the identification of the attacker. This represents a scenario in which an attacker is detected, but positive hostile identification is delayed, potentially due to the need for interaction with a manned control station prior to weapons release authorization. In Model 1.0, the TRUCCs could start firing at the attackers as soon as they were detected because classification occurred at the same time as detection. That assumes that the unmanned system has the authority to classify an inbound track as hostile and open fire. This assumption represents the least stressing case, because no time delay is generated by the need for human decision, or by communication delays. In order to better understand the effects of that assumption a new experiment was designed and implemented. The characteristics of the TRUCC and attackers were the same as in Model 1.0. A delay of zero, five and ten seconds was implemented before the attackers were classified as enemies.

2. Design of Experiments

In order to examine all fifteen possible attacker/delay combinations a quarter-factorial experimental design using the seven TRUCC factors was implemented. This design resulted in 32 scenarios or data points for all fifteen combinations. The blue forces referenced in the Pareto charts represent the TRUCC fleet.

G. MODEL 1.1 RESULTS

The following figures 61 through 75 are screen captures from JMP®, as such they were not edited to change the number of significant figures. Additionally the TRUCC fleet was modeled as the “blue” force, so the number of TRUCCs appears as the “number of blue” in the following Pareto charts.

1. Dumb Missile Time Delay Results

Figures 61, 62, and 63 are the Pareto charts for the Dumb Missile scenario with 0, 5, and 10 second delays.

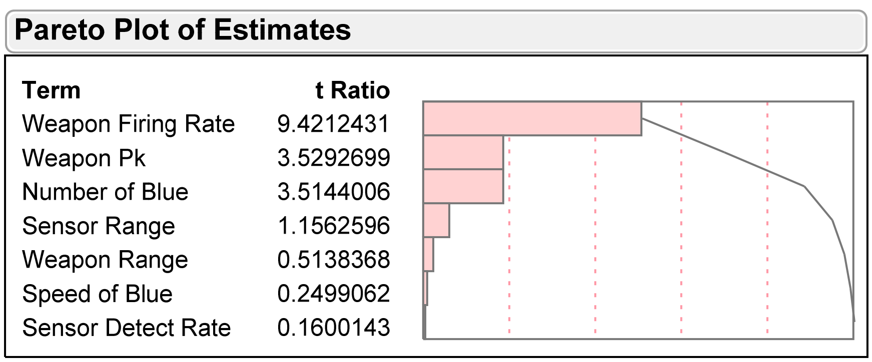

Figure 61. Dumb ASCM 0 Second Delay

Pareto Plot of Estimates

Term	t Ratio
Weapon Firing Rate	2.229361
Sensor Range	2.229361
Weapon Range	1.752857
Weapon Pk	1.752857
Number of Blue	1.650749
Sensor Detect Rate	0.034036
Speed of Blue	-0.034036

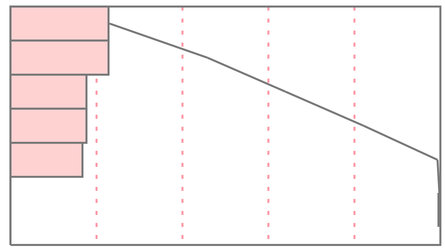

Figure 62. Dumb ASCM 5 Second Delay

Pareto Plot of Estimates

Term	t Ratio
Sensor Range	4.843659
Weapon Firing Rate	3.883900
Weapon Pk	1.582113
Number of Blue	1.570423
Weapon Range	1.123860
Sensor Detect Rate	0.099512
Speed of Blue	-0.042523

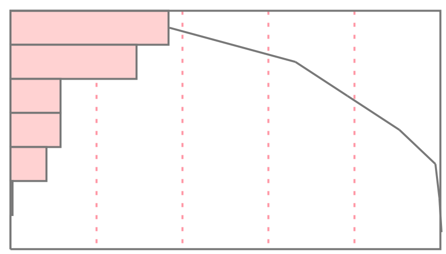

Figure 63. Dumb Missile 10 Second Delay

A clear indication from the plots for Dumb ASCM scenarios is that sensor range becomes increasingly important as the classification delay increases. With no delay, the TRUCCs can react immediately on the hostiles. Due to this there is a significant tradeoff between sensor range and the human or machine agent's ability to classify a threat. Autonomous machines will have no advantage over human operators unless they are able to classify and act upon a threat faster than a human.

2. Dumb LSF Time Delay Results

Figures 64, 65, and 66 are the Pareto charts for the Dumb LSF scenario with 0, 5, and 10 second delays.

Term	t Ratio
Weapon Firing Rate	12.26208
Number of Blue	4.52207
Weapon Pk	3.65224
Sensor Range	1.47745
Speed of Blue	0.38007
Sensor Detect Rate	0.31156
Weapon Range	-0.04404

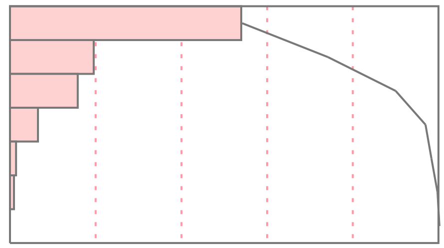

Figure 64. Dumb LSF 0 Second Delay

Term	t Ratio
Weapon Firing Rate	11.62207
Number of Blue	4.35029
Weapon Pk	3.47682
Sensor Range	1.63815
Speed of Blue	0.40047
Sensor Detect Rate	0.36555
Weapon Range	-0.27152

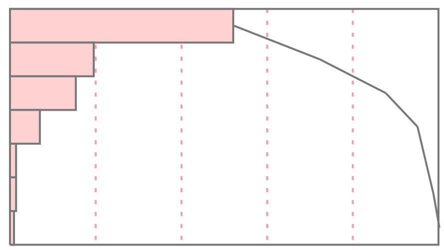

Figure 65. Dumb LSF 5 Second Delay

Term	t Ratio
Weapon Firing Rate	11.14164
Number of Blue	4.04584
Weapon Pk	3.30266
Sensor Range	1.75341
Weapon Range	-0.37213
Speed of Blue	0.29542
Sensor Detect Rate	0.28996

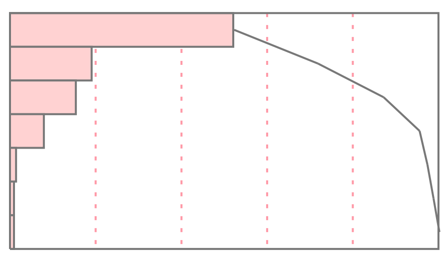

Figure 66. Dumb LSF 10 Second Delay

For the Dumb LSF case, time delays up to 10 seconds have no effect on the order of factor's importance. This makes sense as the LSFs are much slower than the missile threat and therefore sensor range does not become an significant factor. Obviously, with longer delay durations (not evaluated here due to our estimation that 10 seconds is the maximum relevant delay) sensor range will become important, as with the missile case.

3. Smart LSF Time Delay Results

Figures 67, 68, and 69 are the Pareto charts for the Dumb LSF scenario with 0, 5, and 10 second delays.

Term	t Ratio
Weapon Firing Rate	12.37048
Number of Blue	4.64042
Weapon Pk	3.57230
Sensor Range	1.50242
Speed of Blue	0.99172
Sensor Detect Rate	-0.13947
Weapon Range	-0.11798

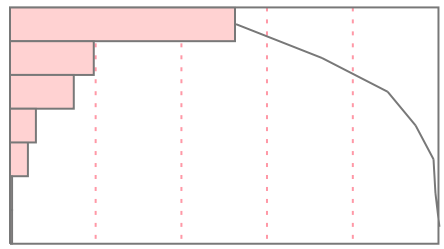

Figure 67. Smart LSF 0 Second Delay

Term	t Ratio
Weapon Firing Rate	12.50632
Number of Blue	4.54345
Weapon Pk	3.59003
Sensor Range	1.90612
Speed of Blue	1.10823
Weapon Range	-0.40083
Sensor Detect Rate	-0.18545

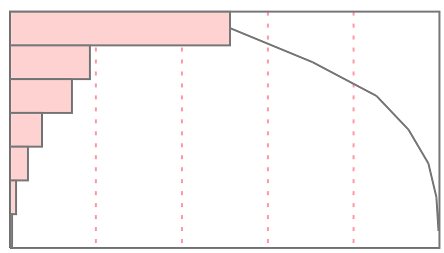

Figure 68. Smart LSF 5 Second Delay

Term	t Ratio
Weapon Firing Rate	12.19565
Number of Blue	4.63659
Weapon Pk	3.57297
Sensor Range	2.02272
Speed of Blue	1.36126
Weapon Range	-0.71213
Sensor Detect Rate	-0.03606

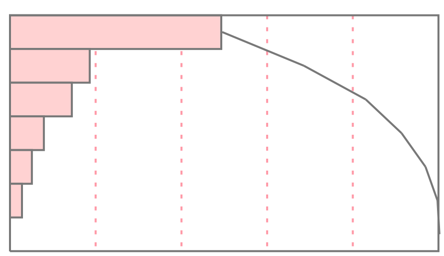

Figure 69. Smart LSF 10 Second Delay

Adding delays in the Smart LSF scenarios has little effect upon the importance of the factors for the same reasons discussed in the Dumb LSF section.

4. Dumb FAC/FIAC Time Delay Results

Figures 70, 71, and 72 are the Pareto charts for the Dumb LSF scenario with 0, 5, and 10 second delays.

Term	Orthog Estimate
Number of Blue	10.73851
Weapon Range	8.21988
Weapon Pk	6.76849
Weapon Firing Rate	5.00890
Sensor Range	2.07113
Speed of Blue	-0.03600
Sensor Detect Rate	0.03293

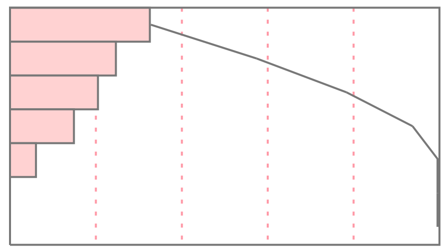

Figure 70. Dumb FAC/FIAC 0 Second Delay

Term	Orthog Estimate
Sensor Range	10.06400
Number of Blue	6.80155
Weapon Range	6.39711
Weapon Pk	4.61070
Weapon Firing Rate	4.49376
Sensor Detect Rate	0.93950
Speed of Blue	-0.64900

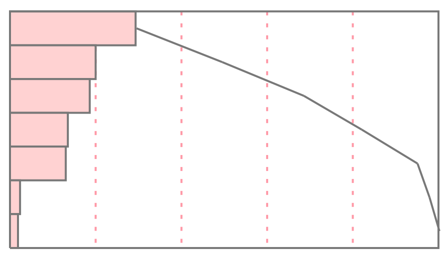

Figure 71. Dumb FAC/FIAC 5 Second Delay

Term	Orthog Estimate
Sensor Range	15.15370
Weapon Range	7.98769
Number of Blue	3.46514
Weapon Firing Rate	1.79406
Weapon Pk	1.78483
Sensor Detect Rate	-0.58038
Speed of Blue	-0.21849

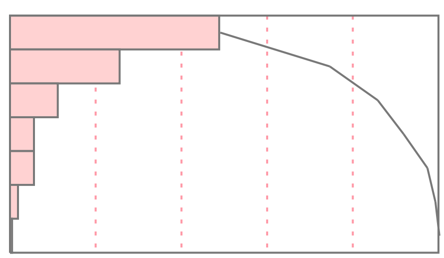

Figure 72. Dumb FAC/FIAC 10 Second Delay

For the Dumb FAC/FIAC scenarios as delay increases sensor range becomes more important on the account of decreasing “number of blue” importance. The FAC/FIAC is the slowest moving threat compared to the missiles and LSFs. This is why the number of TRUCCs is important in the zero delay scenario, as the TRUCCs have sufficient time to make use of all defending forces, even with short weapon ranges. As the time delay grows, this factor is reduced in importance and the early warning given by a longer sensor range increases in importance.

5. Smart FAC/FIAC Time Delay Results

Figures 73, 74, and 75 are the Pareto charts for the Dumb LSF scenario with 0, 5, and 10 second delays.

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Weapon Range	9.376198
Number of Blue	8.382150
Weapon Pk	5.113528
Weapon Firing Rate	3.893692
Sensor Range	-2.500103
Speed of Blue	-0.942573
Sensor Detect Rate	0.756705

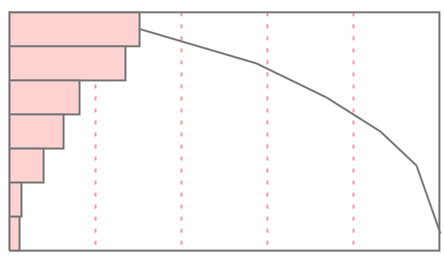

Figure 73. Smart FAC/FIAC 0 Second Delay

Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Weapon Range	7.9167329
Number of Blue	7.3932821
Sensor Range	7.0853032
Weapon Pk	5.2046160
Weapon Firing Rate	5.0156705
Sensor Detect Rate	2.0873240
Speed of Blue	0.0544680

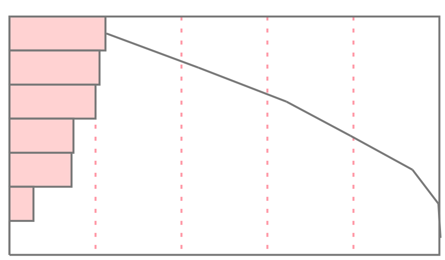

Figure 74. Smart FAC/FIAC 5 Second Delay

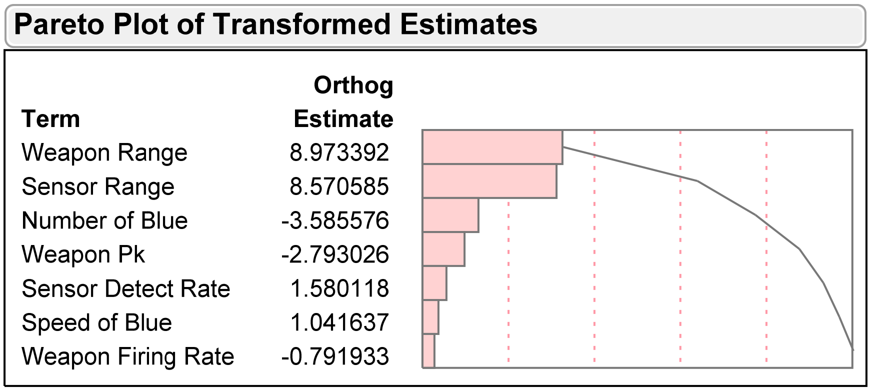

Figure 75. Smart FAC/FIAC 10 Second Delay

In the smart FAC/FIAC scenario, as with the dumb FAC/FIAC scenario sensor range becomes more important with increasing delays. In this instance though, weapon range remains the most important factor as the delay increases. This is due to the maneuvers performed by the smart FAC/FIACs attempting to find a gap in the defenders.

H. MODEL 1.2 DESIGN

Model 1.2 is an experiment to examine the effects of scalability upon system performance. The minimum force ratios identified in the prototype design evaluation experiment were used for this purpose (Table 32). The force ratio between the TRUCCs and the attackers was held constant while the total number of actors was multiplied by two, three, and five. Each of these scenarios was run 100 times and the average casualties for the attacker were recorded.

Table 32. Required Force Ratios

	Required Force Ratio		
Threat	Small	Medium	Large
Dumb Missle	0.5333	0.2333	0.05
Smart LSF	0.217	0.2	0.05
Dumb LSF	0.25	0.11667	0.05
Smart FAC/FIAC	0.1	0.05	0.05
Dumb FAC/FIAC	0.08333	0.05	0.05

The specific number of Small, Medium, Large, and Attackers required for each threat and multiplier is summarized in Table 33.

Table 33. Scalability Experiment Force Strengths

Dumb Missile	Number of Agents			
Multplier	Small	Medium	Large	Red
1	32	14	3	60
2	64	28	6	120
3	96	42	9	180
5	160	70	15	300
SMART LSF	Number of Agents			
Multplier	Small	Medium	Large	Red
1	13	12	3	60
2	26	24	6	120
3	39	36	9	180
5	65	60	15	300
Dumb LSF	Number of Agents			
Multplier	Small	Medium	Large	Red
1	15	7	3	60
2	30	14	6	120
3	45	21	9	180
5	75	35	15	300
Smart FAC/FIAC	Number of Agents			
Multplier	Small	Medium	Large	Red
1	6	3	-	60
2	12	6	-	120
3	18	9	-	180
5	30	15	-	300
Dumb FAC/FIAC	Number of Agents			
Multplier	Small	Medium	Large	Red
1	6	3	-	60
2	12	6	-	120
3	18	9	-	180
5	30	15	-	300

I. MODEL 1.2 RESULTS

The red attack force was destroyed 100% of the time regardless of the multiplier used in every scenario. From these results it is safe to conclude that the TRUCC system performance is approximately linear if the force ratio is held constant. It is likely that due to the three-dimensional nature of the missile and LSF attacks that the required force ratios to ensure red destruction would decrease as more reds attacked since more targets would be available. Unfortunately MANA is a two-dimensional simulation and is unable to assist in investigating the effect any further.

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XIII. OPERATIONAL AVAILABILITY TECHNICAL COMPENDIUM

Operational Availability as defined by OPNAVINST 3000.12A is *the probability that the system will be ready to perform its specified function, in its specified and intended operational environment, when called for at a random point in time.* This definition of operational availability accurately reflects the real-world operating environment and, therefore, is the preferred and most readily available means for which to formulate metrics that assess the quantitative performance of a given system. Further, the tools and models of operational availability provide a means to predict and assess system performance and readiness during deployment and operations/maintenance cycles. More specifically, operational availability consists of a probability function that includes reliability, maintainability and supportability components: System Up Time divided by the Total Time, where Total Time represents two parameters, UP time and DOWN time. UP time is the time a system is operational between failures. DOWN time is the time the system is not operational.[79]

Ao = System Up Time / Total Time (Up Time + Down Time).

For this study, Ao also takes into account logistics time. This inclusion of Ao in rests on the assumption that all parts required for repairs are deployed with the TRUCCs, thereby negating the effects of logistics down time inherent with the researching, ordering, and waiting for repair parts delivery.

A. MODEL PURPOSE AND ASSUMPTIONS

The purpose of the model was to simulate TRUCCs operating in a forward deployed and minimally manned location. The model captured all of the elements concerning the operational availability of the TRUCCs including: amount of time to perform maintenance, amount of time to refuel each TRUCC,

[79] (United States Navy, 2011)

number of hours before routine maintenance must be performed, start-up operational availability of the TRUCCs, and endurance time or the time required for the TRUCCs to perform their mission.

The term “maintenance” encompasses preventative and corrective maintenance. Preventative maintenance includes, but is not limited to, periodic inspection, calibration, and scheduled replacement of fluids or components.[80] Corrective maintenance includes, but is not limited to, the emergent repair of failed systems or components.[81] The model may account for these concepts in separate areas; however it satisfies the aforementioned definition of operational availability.

The term start-up operational availability refers to the TRUCC’s ability to proceed onto mission from a standby status. This term takes into account corrective maintenance, cannibalization of parts, delay times of diesel engine start-up, and any other maintenance being performed on the TRUCCs while in standby that was not completed in the maintenance area.

The TRUCC must achieve an unprecedented level of reliability for maritime vehicles to support Combat Operations. Unlike manned vessels, the TRUCC was not assumed to have dedicated onboard personnel to troubleshoot equipment problems, perform scheduled preventative maintenance, or make repairs to the system(s) while underway in a mission critical environment.

Although unprecedented in the maritime domain, this high level of reliability is currently achieved in mature unmanned aerial vehicles. For example, the Extended Range/Multi-Purpose Unmanned Aerial System (ER/MP UAS) regularly achieved an overall reliability greater than 0.9.[82] Using the aforementioned examples, the TRUCC system was assumed to have achieved a

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[80] (Operations, 2000, p. 154)

[81] (O'Rourke, 2008, p. 5)

[82] (General Atomics Aeronautical Systems, 2010)

reliability of no less than 0.95 including deployment, completing the mission, and returning to base. This reliability assumption was chosen for illustrative purpose only. Detail level design will determine the actual system reliability requirement.

B. MODEL INPUTS AND OUTPUTS

The inputs to the model were taken from the Mission Vehicle Group, via ship synthesis, and are:

- Projected TRUCC endurance times plus variances.
- Number of required TRUCCs on station to successfully fulfill a desired mission.

These inputs generate the following outputs:

- Number of TRUCCs required in inventory to fulfill the requisite number of TRUCCs on station.
- Required Ao to support the TRUCC systems.

C. OPERATIONAL AVAILABILITY MODEL

Using ExtendSim® 8.0 stochastic modeling software allowed for analysis of wide variations within the model. For example, several functions within the model required different statistical distributions and the ExtendSim® software provided for manipulation of the inputs and outputs for these functions. The software allowed us to vary the statistical distribution means and standard deviations in order to for us to capture the most realistic scenario for the DRM. A functional flow block diagram of the ExtendSim® model is represented in Figure 76 and discussed in detail in the following paragraphs.

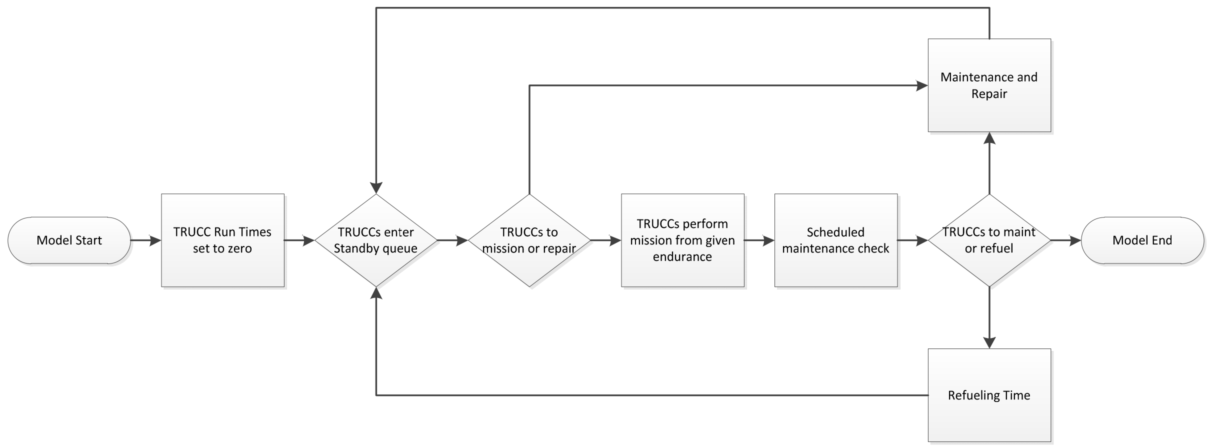

Figure 76. Functional Flow Block Diagram

The ‘Model Start’ block is the beginning of the model. The initial number of TRUCCs in inventory is read from an Excel® database and imported into the model. This block also starts the clock.

The model then flows into the “TRUCC Run Times set to zero” block. This block sets all of the TRUCC operating hours to zero and was done to represent and capture the need for planned maintenance accurately. This block also simulates a new batch of TRUCCs arriving in theater and being placed into service.

From here the newly arriving TRUCCs flow into the “TRUCCs enter Standby queue” block. This block represents the TRUCCs in an operational standby configuration awaiting an assignment to proceed to mission. TRUCCs enter the standby queue, (1) upon model initialization, (2) after maintenance or repair is conducted, or (3) after they have been refueled and remain in this queue until a need arises for them to proceed to a mission.

From here the TRUCCs, in stand-by configuration, flow into the “TRUCCs to mission or repair” block. This block represents the probability that a TRUCC will be operationally available after it has been placed in standby. This block refers to the start-up operational availability of the TRUCCs. The TRUCCs enter this block and are either (1) found suitable to proceed to mission or (2) they are sent for repairs. This process allows for consideration of additional variables related to unplanned maintenance, such as:

- TRUCCs failure to start
- Time required to heat up the lube oil
- Time required to heat up the engine coolant
- Time required to heat up the intake air
- Time required to heat up the battery
- Routine maintenance being accomplished pierside rather than in the maintenance bays[83]
- Cannibalization of TRUCC parts to ensure enough TRUCCs are mission ready

This block also simulates the start-up operational availability of the TRUCCs and accepts any combination of probability values so long as the total probability (probability of success and failure) adds to one.

From here, the model flows into the "TRUCCs perform mission from given endurance" block for the TRUCCs that were suitable to proceed onto mission. This block represents the required number of TRUCCs out on mission for a given endurance time. Given they are suitable to proceed from the previous block, they enter this block and perform their mission for the given endurance hours that are *normally distributed* with a standard deviation of 30 minutes. This distribution allows for small variations in the (1) amount of time required to be out on mission, (2) the time required to transit to their station, and (3) to account for TRUCCs

[83] (United States Navy, 2005, p. 233)

being relieved at different times in order to maintain the required number of TRUCCs out on mission. The endurance times are varied and are read from an Excel® database and imported into the model.

From here the model flows into the “Scheduled maintenance check” block. This block represents TRUCCs that are required to have preventative maintenance performed on one of their systems. The model uses a fixed number of 1,500 hours for this block based on oil and oil filter replacement intervals for a diesel engine that does not have a dedicated onboard lube oil purifying system.[84] Most of the information for engines was proprietary, forcing the use of analogous information readily available for diesel generators. The assumption was made that once a TRUCC is out on mission, the diesel engine would operate mostly at a constant speed in order to conserve fuel, thus resembling how a generator is operated. It was determined that this scheduled maintenance was the most common and allowed for other preventative maintenance to be performed concurrently. When the TRUCCs enter this block, their operating hours are checked to determine the requirement for preventative maintenance.

From here the model flows into the “TRUCCs to maintenance or refuel” block. This block represents TRUCCs returning from a mission; they either proceed to preventative maintenance or are refueled. If a TRUCC’s operating hours are greater than the specified number of hours required for preventative maintenance, it will be sent to a preventative maintenance queue. Only the TRUCCs that were over the required number of hours were sent to maintenance, because the number of mission hours are small compared to the hours required to perform the maintenance.

From here, TRUCCs not requiring preventative maintenance are routed into the “Refueling Time” block. This block represents the refueling of TRUCCs

[84] (United States Navy, 2005, p. 233)

following a mission, simulated using a normal distribution with a mean of 45 minutes and a standard deviation of 6 minutes; this distribution captures the minor differences associated with amounts of fuel dispensed and times required to transit to/from the refueling station. The refueling time was based on basic ship synthesis analysis conducted by the Mission Vehicle Group.

From here the model flows back into the “TRUCCs enter Standby queue” block. The “Maintenance and Repair” block receives TRUCCs if repairs or preventative maintenance are required and represents the time required to perform (1) routine maintenance, (2) troubleshooting, and (3) conduct repairs on the TRUCCs. Here, maintenance and repair actions are grouped into one term called “maintenance time”. This block has the capacity to service a maximum of only five TRUCCs at any given time; this restriction captures the reality of a forward operating base with limited facilities and minimum manning in accordance with the DRM.

The time to perform the maintenance or repairs is read into the model from an Excel® database and utilizes a Poisson distribution with a varied expected value for each TRUCC. A Poisson distribution was used in order to explore the impact of maintenance on the availability of the TRUCCs. This distribution generated a range of discrete maintenance times required to perform the maintenance. The Poisson distribution accounted for vast differences in the arrival and departure times to perform repairs and maintenance. This distribution also takes into account that each occurrence for repair or maintenance is completely independent from the previous occurrence. There are many different distributions that could have been chosen to model the maintenance times for the TRUCCs. To validate the Poisson distribution, the group compared these outputs to log-normal and Weibul distributions for a limited number of simulations. No significant difference was found in model output regardless of distribution chosen. The discrete Poisson output performs similarly to other continuous distributions while allowing for slightly simplified analysis appropriate for initial sensitivity determination. A representative histogram, outputted from

ExtendSim®, is shown as figure 77. Note that the bins lie on integer values but the ExtendSim® screenshot X axis values were determined based the size of the range and number of divisions. Because of this issue the integer values on not displayed on the X axis.

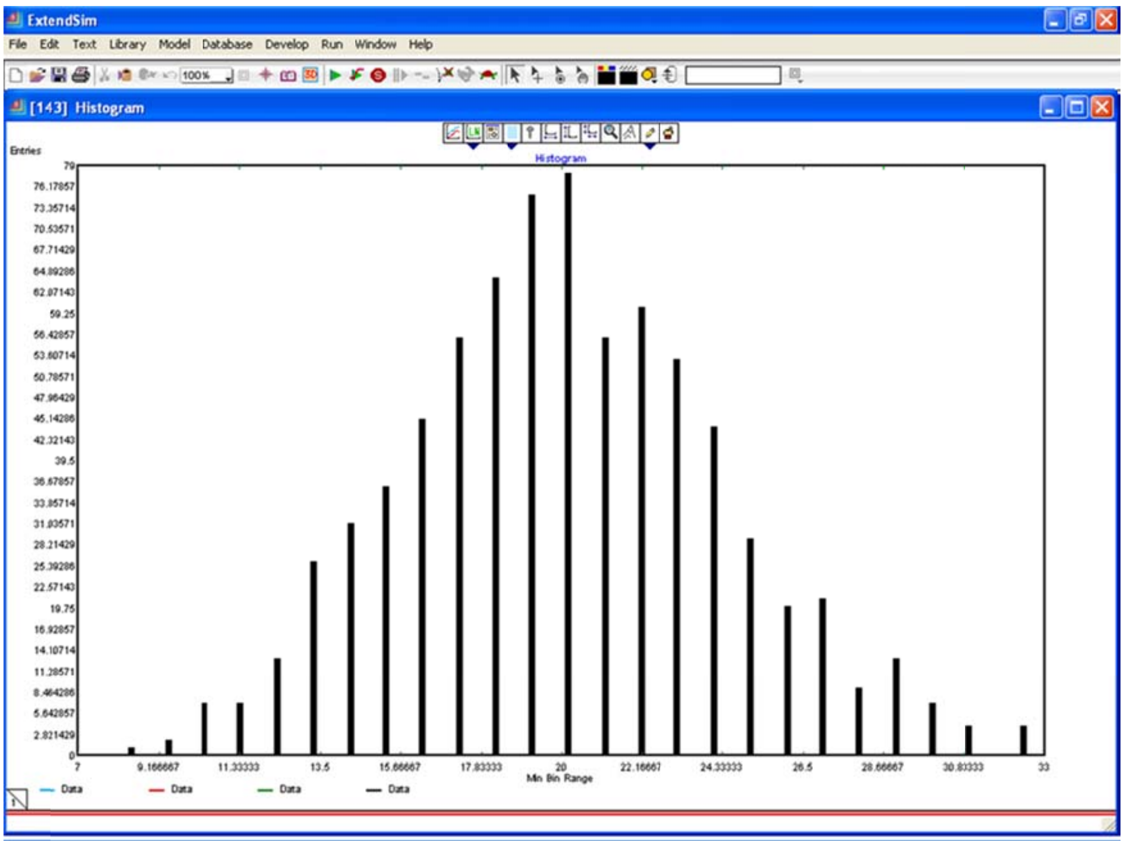

Figure 77. ExtendSim Output Histogram for Poisson Distribution

Figure 77 shows the Poisson distribution for the Large TRUCC variant with an expected maintenance time of 20 hours over the course of 100,000 hours. The figure's X-axis is the number of maintenance hours performed and the Y-axis is the number of occurrences for each bin. Before exiting this block all TRUCC operating hours are reset to zero to account for the preventative maintenance being performed. The time in this block also accounts for the refueling of each TRUCC.

From this block the model flows back into the “TRUCCs enter Standby queue” block. The final block is the “Model End” block and is set to run for a specific number of hours before the model is complete. Therefore, the simulation ends when the time limit is reached and one complete run is recorded. If required, the simulation will restart. If not, the simulation ends.

D. OPERATIONAL AVAILABILITY MODEL SCREENING EXPERIMENT DESIGN

Using JMP®, a design of experiments was conducted on the model input factors of endurance, refueling, and maintenance. From this DOE, a randomized experiment was formulated using three factors, each with nine levels, resulting in a 9x9x9 factorial design randomized screening experiment, totaling 729 total runs, to determine which (if any) of the factors were significant. The other input variables (reliability, number of hours for the model, number of TRUCCs that can be on mission, the number of TRUCCs that can be repaired or maintained at the same time, and the number of hours before routine maintenance) were held constant within the model. The screening experiment used an assumed .8 start-up operational availability factor, 5,000 hours for the run time, 30 TRUCCs required on mission, 5 TRUCCs repaired at a time, and 1,500 hours for routine maintenance.

Table 34. Statistical Distribution Table

Statistical Distribution Table			
Factor	**Distribution Type**	**Mean**	**Standard Deviation**
Endurance	Normal	Varied between TRUCC Variants	30 minutes
Refueling	Normal	45 minutes	6 minutes
Maintenance	Poisson	Varied between TRUCC Variants	--

The model received its endurance and refueling time inputs from the TRUCC design model considered to be normally distributed using the parameters listed in Table 34. This allowed flexibility for transit times and connect/disconnect times during refueling. These numbers were then varied for the three different sizes of TRUCCs and a range of both factors calculated.

The times required to perform preventative maintenance and repairs were distributed between 10 to 90 hours using a Poisson distribution, and varied between the three sizes of TRUCCs. This distribution allowed for consideration of occasional lengthy repairs.

Maintenance Times were determined by taking into account minor adjustments to and potential replacement of essential systems due to catastrophic failure. It is assumed that essential systems are more likely be replaced rather than repaired and in turn will shorten repair times.

The requisite high level of reliability associated with the TRUCC mandates a tight bound on the distribution and is further supported using the assumption that each deploying TRUCC must be accompanied by its own replacement parts kit. This kit must contain adequate replacement parts and special tools to sustain the system for the duration of its deployment. Additionally, greater organization level (O-Level) maintenance will exist, compared to Intermediate (I-Level) maintenance or Depot (D-Level) maintenance, at forward deployed locations. These terms are widely used in the Naval Aviation Community. Table 35 describes what each level of maintenance entails.

Table 35. Maintenance Description (from Navy Aviation Technical Publication 14001-234)

O-Level Maintenance	I-Level Maintenance	D-Level Maintenance
Inspection, operation, and servicing as defined and required by PMS	Repair, test, inspection, and modification of components and related equipment	Supports O and I-Level Maintenance by providing engineering assistance
Corrective and preventive maintenance, including on-equipment repair and removal/replacement of defective parts	Manufacture of selected nonavailable parts	Performs maintenance beyond the capability of O or I-Level maintenance
Incorporation of techinical directives (TDs), within prescribed limitations	Incorporation of techinical directives (TDs), within prescribed limitations	Performed by shipyards, repair facilities, warfare centers, and deployable repair teams from specified depots
Record keeping and reports writing	Calibration of designated equipment	

For the Medium- and Small- sized TRUCCs, factors of 0.67 and 0.1 respectfully were applied to the maintenance times for the large variant due to the level of complexity decreasing and the ease of maintenance increasing as the size of the TRUCC decreased.

Table 36. Platform Operational Availability [85], [86], [87], [88], [89]

Platform	Operational Availability
Coastal Patrol Craft (PC)	0.62
Ohio Class Nuclear Powered Submarine (SSBN)	0.68
Forward deployed Guided Missile Destroyers (DDG)	0.2
Los Angeles Class Nuclear Powered Submarine (SSN)	0.6
ER/MP Unmanned Aerial System (UAS)	0.9
Littoral Combat Ship (LCS)	0.67
MH-60R Multi-Mission Helicopter	0.75
MV-22 Osprey Tilt-Rotor Aircraft	0.62

Research was conducted to determine the required level of start-up availability for the TRUCC and its supporting systems. Technically specific data was either classified or proprietary; however, open-source documentation revealed the overall operational availability factors shown in Table 36 and represent useable unclassified data for DoD manned and unmanned systems; the most reliable systems were between 0.6 and 0.9. There is no available data for start-up Ao, but the gathered data does give insight into and includes the start-up Ao. Therefore, a value of 0.8 was used for illustration purpose only. The actual operational requirement will be determined through detailed design studies. The major takeaway of this section were obtained through the variation of the operational availability value used in the model.

85 (Congressional Budget Office, 2007)

86 (General Atomics Aeronautical Systems, 2010)

87 (Baggett, Logistical Analysis of the Littoral Combat Ship (LCS) Operating Independently in the Pacific, 2008, p. xvi)

88 (Director, Operational Test and Evaluation, 2006, p. 273)

89 (Gertler, 2011, p. 9)

E. OPERATIONAL AVAILABILITY MODEL SCREENING EXPERIMENT RESULTS

The actual number of TRUCCs on mission was insignificant to model outputs, because the goal of the screening experiment was designed to assess the weight of the variables within the model. Therefore, the assumption was made that the number of TRUCCs in inventory merely needed to support the number required for a mission and would subsequently translate into a force ratio for the various sizes of TRUCCs and their respective missions.

A run-time of 5,000 hours was sufficient to stress the TRUCCs and forced them to require maintenance and allowed the model to successfully progress through a warm-up period and reach a steady state of operation. Additionally, the long run time presented a viable opportunity to analyze any significant trends or factors that arose within the model

Finally, refueling times had no significant impact on the model. Once the models are refined, the refueling values will be held constant and only the maintenance and endurance times will be manipulated for further analysis. It is important to note that the time to perform repairs, time to conduct troubleshooting, and time to perform planned maintenance were consolidated into one term labeled “maintenance time.”

1. Large TRUCC

The screening experiment revealed that 37 TRUCCs were required in inventory to achieve an average of 30.0 TRUCCs on mission. It also revealed that supporting the Large TRUCC variants with endurances less than 22.6 hours and maintenance intervals above 40 hours required greater than 50 TRUCCs in inventory; this was deemed impractical because of the large number of TRUCCs required in inventory to accommodate such high maintenance times. Table 37. only considers the TRUCC variants that meet the required 30.0 average and depicts the number of TRUCCs required in inventory, the average maintenance times required to support them, and the minimum and maximum value combinations required to meet mission requirements.

Table 37. Maximum Allowable Maintenance Times for given Inventory, Large

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
37	66.3	10	76	10	53.1	10
38	60.4	10	76	10	45.5	10
39	59.1	11.4	76	20	37.9	10
40	55.8	11.4	76	20	30.3	10
41	55.6	12.1	76	20	30.3	10
42	57.6	13	68.4	30	30.3	10
43	58.5	13	76	30	22.6	10
44	57.5	13.9	76	30	22.6	10
45	56.3	16.4	76	30	22.6	10
46	55.8	16.5	76	30	22.6	10
47	56.4	17.2	76	40	22.6	10
48	56.5	17.6	76	40	22.6	10
49	56.5	17.7	76	40	22.6	10
50	56.4	17.9	76	40	22.6	10

Maintenance times must average 40 hours or less for efficiency. Additionally, achieving 76-hour endurance required TRUCC inventories greater than 36. An example of how to interpret Table 37 is by looking at the row with 40 TRUCCs in inventory and following that row to the right.

The average endurance hours observed was 55.8 hours with 11.4 hours of associated average maintenance. The maximum and minimum combinations of endurance and maintenance time observed were 76 hours of endurance with 20 hours of maintenance and 30.3 hours of endurance with 10 hours of maintenance respectively. In summary, the number in inventory is the critical variable in achieving the overall endurance and maintenance times given a number of TRUCCs required for a specific mission.

2. Medium TRUCC

For the Medium TRUCC variant, 41 TRUCCS were required in inventory to achieve an average of 30.0 TRUCCs on mission. Once again, Table 38 only considers the TRUCC variants that meet the required 30.0 average and depicts the number of TRUCCs required in inventory, the average maintenance times required to support them, and the minimum and maximum value combinations required to meet mission requirements.

Table 38. Maximum Allowable Maintenance Times for given Inventory, Medium

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
41	90.4	7.9	133	13.2	52	6.6
42	88.3	12.5	133	39.6	25	6.6
43	90.2	15.6	133	46.2	25	6.6
44	94	20.2	133	59.4	25	6.6
45	94.8	22.7	133	59.4	25	6.6
46	94.3	23.5	133	59.4	25	6.6
47	94.3	24.6	133	59.4	25	6.6
48	93.9	25.5	133	59.4	25	6.6
49	93.9	26.2	133	59.4	25	6.6
50	93.9	26.6	133	59.4	25	6.6

Maintenance hours were capped at 40 hours or less in order to be efficient. The Medium variant achieved a 75% increase in maximum endurance hours (from 76 to 133) across the board for all inventories greater than 41.

The maximum and minimum combinations of endurance and maintenance time that were observed during the DOE were 133 hours of endurance with 59.4 hours of maintenance 25 hours of endurance with 6.6 hours of maintenance respectively. Again, the number in inventory is the critical variable to achieving the desired endurance and maintenance times for a requisite mission.

3. Small TRUCC

The number of Small TRUCCs required in inventory to achieve an average of 30.0 TRUCCs on mission was 35. Again, Table 39 only considers TRUCC variants that meet the required 30.0 average and depicts the number of TRUCCs required in inventory, the average maintenance times required to support them, and the minimum and maximum value combinations required to meet mission requirements.

Table 39. Maximum Allowable Maintenance Times for given Inventory, Small

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
35	21.3	1	22.2	1	20.3	1
36	19.7	1.1	24	2	16.5	1
37	18	1.3	24	2	14.6	1
38	18.63	1.65	24	3	14.6	1
39	18.5	1.9	24	4	12.8	1
40	18.1	2.2	24	5	9	1
41	17.9	2.8	24	6	9	1
42	17.9	3.3	24	7	9	1
43	18	3.7	24	8	9	1
44	18	4	24	9	9	1
45	17.9	4	24	9	9	1
46	17.8	4.3	24	9	9	1
47	17.8	4.4	24	9	9	1
48	17.7	4.4	24	9	9	1
49	17.7	4.4	24	9	9	1
50	17.7	4.4	24	9	9	1

For this variant, maintenance must average 9 hours or less for efficiency. Also, 24-hour endurance was achievable for all TRUCC inventories greater than 37. The maximum and minimum combinations of endurance and maintenance time that were observed were 24 hours of endurance with 5 hours of maintenance and 9 hours of endurance with 1 hour of maintenance respectively. Again, the number in inventory was critical to achieving the desired number of operational vessels.

F. REFINED DOE MODEL

After analyzing the data extracted from the screening experiment, the maintenance times for the model were refined for the three TRUCC size variants. A customized one factor DOE with 81 levels was generated using 1x81 factorial design randomized for the refinement experiment; only maintenance times varied. The goal for the refinement was to determine the number of TRUCCs required for each variant given a specific threat.

The following variables were held constant due to the focused interest in the number of overall TRUCCs required in inventory with a constant start-up operational availability of 0.8: refueling time, number of running hours for the model, number of TRUCCs that can be on mission, the number of TRUCCs that can be repaired or maintained at the same time, the refueling times for each variant, the endurance times for each variant, and the number of hours before routine maintenance. This DOE was run with an assumed 45 minute refueling time, 5,000 hours run time, a 5 TRUCC cap on the number of vessels under repair, 0.8 start-up operational availability, and 1,500 hours for routine maintenance.[90]

1. Large TRUCC for Low Slow Flyer, FAC/FIAC, and Cruise Missile threats

The refined experiment showed that the minimum number of TRUCCs required in inventory to achieve an average of 3.0 TRUCCs on mission was four. To maintain consistency with the baseline model, Table 40 considers only the TRUCC variants that meet the required 3.0 average and depicts the number of TRUCCs required in inventory, the average maintenance times required supporting them, and the minimum and maximum value combinations required to meet mission requirements.

Table 40. TRUCC Endurance and Maintenance

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
4	88.1	12	88.1	17.5	88.1	10
5	88.1	23.7	88.1	40	88.1	10
6	88.1	25	88.1	40	88.1	10

As depicted, Table 40 maintenance times averaged 25 hours or less and averaged 12 hours for the worst-case scenario of only one spare TRUCC in inventory. Increasing the number of TRUCCs in inventory by two drastically increased the allowable mean maintenance time from 17.5 to 40 hours.

With five TRUCCs in inventory, the average endurance was 88.1 hours with an average maintenance time of 23.7 hours. The maximum and minimum

[90] (Caterpillar Corporation, 2011, p. 2)

combinations of endurance and maintenance time were 88.1 hours of endurance with 40 hours of maintenance and 88.1 hours of endurance with 10 hours of maintenance respectively. Again, the number of TRUCCs in inventory affects how much maintenance time can be afforded to the TRUCCs and vice versa.

A linear regression analysis was then performed on the data output from the model to derive endurance times and the number of TRUCCs required on mission. Due to time constraints, the model was run only until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. The derived equation does provide strong insight into the relationship between the number of TRUCCs required in inventory given and average maintenance times.

The results were an achieved R squared value of 0.82 with a p-value for the average maintenance time of 0.275 (slightly higher than the accepted criteria of 0.20). Since, the p-value is higher than 0.20 it shows that the data for maintenance times may not be statistically significant in determining the number of TRUCCs required in inventory. The output from the regression is shown in Figure 78:

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.908					
R Square	0.824					
Adjusted R Square	0.648					
Standard Error	0.593					
Observations	3					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1.648	1.648	4.688	0.275	
Residual	1	0.352	0.352			
Total	2	2				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.434	1.233	1.974	0.299	-13.238	18.107
Average Maintenance Time (hrs)	0.127	0.059	2.165	0.275	-0.617	0.871

Figure 78. Regression Output

The derived equation is:

$$InventoryofTRUCCs = 2.434 + (.127 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats. The team recommends further analysis to yield a more robust equation.

2. Analysis of Large TRUCCs

Following data collection, TRUCCs were grouped by numbers required in inventory, TRUCCs required on mission, and the average maintenance time factors. A similar regression analysis was conducted to determine the number of TRUCCs required in inventory. The analysis achieved an R squared value of 1.0 with undetermined p-values for the number of TRUCCs required on mission and the average maintenance time. The data used (see Table 41) and the regression output summary (see Figure 79) are shown.

Table 41. Required TRUCCs based on Maintenance Time

TRUCCs in Inventory	TRUCCs Required	Average Maintenance Time (hrs)
4	3	12
5	3	23.7
6	3	25

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	2	1	#NUM!	#NUM!
Residual	0	0	65535		
Total	2	2			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.434	0	65535	#NUM!	2.434	2.434
TRUCCs Required	0.000	0	65535	#NUM!	0.000	0.000
Average Maintenance Time (hrs)	0.127	0	65535	#NUM!	0.127	0.127

Figure 79. Regression Output

These errors were the result of both insufficient data and forcing the number of TRUCCs to a specific value. The minimum number of TRUCCs required to defend against all threats was 3. This resulted in no variation resulting in an R Square value of 1.0. These factors alone cannot be used to determine the amount of large TRUCCs required in inventory. Further analysis is required to analyze the large TRUCC variant in different DRMs in order to gather more data.

3. Medium TRUCC for FAC/FIAC Threat

The minimum number of TRUCCs required in inventory to achieve an average of 3.0 TRUCCs on mission was four. Table 42 considers only the required 3.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 42. Medium TRUCC Maintenance Values

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
4	99.8	11.2	99.8	19.9	99.8	6.6
5	99.8	29.1	99.8	59.6	99.8	6.6
6	99.8	32.1	99.8	59.6	99.8	6.6

As depicted in Table 42, maintenance times averaged 32.1 hours or less and averaged 11.2 hours for the worst-case scenario of only one spare TRUCC in inventory. Adding two extra TRUCCs to the inventory drastically increased the mean maintenance time from 11.2 to 29.1 hours. The maximum combination was 99.8 hours of endurance with 59.6 hours of maintenance and the minimum combination was 99.8 hours of endurance with 6.6 hours of maintenance.

A regression analysis was performed on the data using the derived endurance time and the derived number of TRUCCs required on mission. As for previous variants, the model was run only until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. Subsequently, because only three data points for TRUCCs in inventory and the average maintenance time was collected the regression offers basic insights but could be improved with additional DRM data points. This regression provides insight into the number of TRUCCs required in inventory given an average maintenance time. With an R-squared value of .86 and a p-value for the average maintenance of .249 (slightly higher than the accepted .20), the output from the regression is shown in Figure 80.

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.925					
R Square	0.855					
Adjusted R Square	0.710					
Standard Error	0.538					
Observations	3					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1.710	1.710	5.903	0.249	
Residual	1	0.290	0.290			
Total	2	2				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.0252	0.8702	3.4763	0.1783	-8.0322	14.0825
Average Maintenance Time (hrs)	0.0818	0.0337	2.4295	0.2486	-0.3461	0.5098

Figure 80. Medium TRUCC Regression Output

The derived equation is:

$$InventoryofTRUCCs = 3.025 + \left(.0818 \times AvgMainTime\right)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats. It is the team's recommendation that additional data be collected to yield a more robust equation.

4. Medium TRUCC for Dumb LSF Threat

The minimum number of TRUCCs required in inventory to achieve an average of 7.0 TRUCCs on mission was 10. Table 43 considers only the required 7.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 43. Medium TRUCC Maintenance Values

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
10	99.8	16.2	99.8	39.7	99.8	6.6
11	99.8	20.5	99.8	39.7	99.8	6.6
12	99.8	31.6	99.8	59.6	99.8	6.6
13	99.8	32.4	99.8	59.6	99.8	6.6

As depicted in Table 43, maintenance times averaged 32.4 hours or less and averaged 16.2 hours for the worst case scenario of only 3 spare TRUCCs in inventory. By adding two TRUCCs to inventory the allowable mean maintenance time drastically increased from 16.2 to 31.6 hours. The maximum combination was 99.8 hours of endurance with 39.7 hours of maintenance and the minimum combination was 99.8 hours of endurance with 6.6 hours of maintenance.

A regression analysis was performed on the data using the derived endurance time and the derived number of TRUCCs required on mission. As for previous variants, the model was only run until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. The analysis achieved an R squared value of 0.91, but the p-value for the average maintenance time was 0.045. Since, the p-value is lower than 0.05 it shows that maintenance time is statistically significant in determining the number of TRUCCs required in inventory. The output from the regression is shown in Figure 81.

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.954					
R Square	0.910					
Adjusted R Square	0.865					
Standard Error	0.475					
Observations	4					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	4.549	4.549	20.155	0.046	
Residual	2	0.451	0.226			
Total	3	5				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	7.664	0.887	8.641	0.013	3.848	11.480
Average Maintenance Time (hrs)	0.152	0.034	4.489	0.046	0.006	0.298

Figure 81. Medium TRUCC Regression Output

The derived equation is:

$$InventoryofTRUCCs = 7.664 + (.152 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats.

5. Medium TRUCC for Smart LSF Threat

The minimum number of TRUCCs required in inventory to achieve an average of 12.0 TRUCCs on mission was 17. Table 44 only considers the required 12.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 44. Maintenance Values for Medium TRUCC

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
17	99.8	9.2	99.8	13.2	99.8	6.6
18	99.8	19.7	99.8	33.1	99.8	6.6
19	99.8	30.4	99.8	59.6	99.8	6.6
20	99.8	32.4	99.8	59.6	99.8	6.6

As depicted in Table 44, maintenance times averaged 32.4 hours or less and averaged 9.2 hours for the worst-case scenario of only 5 spare TRUCCs in inventory. By adding seven extra TRUCCs to inventory, the allowable mean maintenance time drastically increased from 9.2 to 30.4 hours. The maximum combination was 99.8 hours of endurance with 59.6 hours of maintenance and the minimum combination was 99.8 hours of endurance with 6.6 hours of maintenance.

A regression analysis was performed on the data using the derived endurance time and the derived number of TRUCCs required on mission. As for previous variants, the model was only run until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. This model achieved an R-squared value of .94 and a p-value of .032. The output from the regression is shown in Figure 82.

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.968					
R Square	0.936					
Adjusted R Square	0.904					
Standard Error	0.400					
Observations	4					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	4.680	4.680	29.279	0.032	
Residual	2	0.320	0.160			
Total	3	5				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	15.828	0.533	29.706	0.00113	13.535	18.120
Average Maintenance Time (hrs)	0.117	0.022	5.411	0.032	0.024	0.209

Figure 82. Medium TRUCC Regression Output

The derived equation is:

$$InventoryofTRUCCs = 15.83 + (.117 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats.

6. Medium TRUCC for ASCM Threat

The minimum number of TRUCCs required in inventory to achieve an average of 14.0 TRUCCs on mission was 20. Table 45 only considers the required 14.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 45. Medium TRUCC Maintenance Values

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
20	99.8	8.6	99.8	13.2	99.8	6.6
21	99.8	20.9	99.8	39.7	99.8	6.6
22	99.8	24.7	99.8	46.4	99.8	6.6
23	99.8	32.1	99.8	59.6	99.8	6.6

As depicted in Table 45, maintenance times averaged 32.1 hours or less and averaged 8.6 hours for the worst case scenario of only 6 spare TRUCCs in inventory. By adding seven extra TRUCCs to inventory, the allowable mean maintenance time drastically increased from 8.6 to 20.9 hours. The maximum combination was 99.8 hours of endurance with 39.7 hours of maintenance and the minimum combination was 99.8 hours of endurance with 6.6 hours of maintenance.

A regression analysis was performed on the data using the derived endurance time and the derived number of TRUCCs required on mission. As for previous variants, the model was only run until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. This model achieved an R-squared value of 0.95 and a p-value of 0.023. The output from the regression is shown in Figure 83.

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.977					
R Square	0.954					
Adjusted R Square	0.931					
Standard Error	0.339					
Observations	4					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	4.770	4.770	41.436	0.023	
Residual	2	0.230	0.115			
Total	3	5				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	18.730	0.463	40.492	0.000609	16.740	20.720
Average Maintenance Time (hrs)	0.128	0.020	6.437	0.0233	0.0426	0.2142

Figure 83. Medium TRUCC Regression Output

The derived equation is:

$$InventoryofTRUCCs = 18.73 + (.1284 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats.

7. Analysis of Medium TRUCCs

Following data collection, Medium TRUCCs were grouped by numbers required in inventory, TRUCCs required on mission, and the average maintenance time factors. A similar regression analysis was conducted to determine the number of TRUCCs required in inventory. The analysis achieved an R squared value of 0.996 with acceptable p-values for the number of TRUCCs required on mission and the average maintenance time. The data used and the regression summary output are shown in Table 46 and Figure 84 respectively.

Table 46. Average Maintenance Time

TRUCCs in Inventory	TRUCCs Required	Average Maintenance Time (hrs)
4	3	11.2
5	3	29.1
6	3	32.1
10	7	16.2
11	7	20.5
12	7	31.6
13	7	32.4
17	12	9.2
18	12	19.7
19	12	30.4
20	12	32.4
20	14	8.6
21	14	20.9
22	14	24.7
23	14	32.1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.998
R Square	0.996
Adjusted R Square	0.996
Standard Error	0.422
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	580.796	290.398	1630.759	2.427E-15
Residual	12	2.137	0.178		
Total	14	582.933			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-2.280	0.427	-5.337	0.000177	-3.211	-1.349
TRUCCs Required	1.514	0.027	57.077	5.520E-16	1.456	1.571
Average Maintenance Time (hrs)	0.119	0.013	9.332	7.521E-07	0.091	0.147

Figure 84. Medium TRUCC Regression Output

The derived equation from the analysis is:

$$InventoryofTRUCCs = -2.28 + (1.51 \times NumberofTRUCCsRequired)(.119 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats.

8. Small TRUCC for FAC/FIAC Threat

The minimum number of Small TRUCCs required in inventory to achieve an average of 6.0 TRUCCs on mission was 11. Table 47 only considers the required 6.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 47. Maintenance Values for Medium TRUCCs

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
11	3.8	1	3.8	1	3.8	1
12	3.8	1.4	3.8	2	3.8	1
13	3.8	2.3	3.8	4	3.8	1
14	3.8	2.8	3.8	5	3.8	1
15	3.8	3.6	3.8	7	3.8	1
16	3.8	3.9	3.8	7	3.8	1

As depicted in Table 47, maintenance times averaged 3.9 hours or less and averaged 1 hour for the worst-case scenario of only 5 spare TRUCCs in inventory. The data reveals that having a mean maintenance time of greater than 7 hours is not feasible without adding 10 additional TRUCCs to inventory. The results also depict that having more than 16 TRUCCs in inventory contributes little added significance. The maximum combination was 3.8 hours of endurance with 7 hours of maintenance and the minimum combination was 3.8 hours of endurance with 1 hour of maintenance.

A regression analysis was performed on the data using the derived endurance time and the derived number of TRUCCs required on mission. As for previous variants, the model was only run until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. This model achieved an R-squared value of 0.99 and a p-value of near zero. The output from the regression is shown in Figure 85:

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.993					
R Square	0.986					
Adjusted R Square	0.982					
Standard Error	0.248					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	17.254	17.254	281.060	0.000	
Residual	4	0.246	0.061			
Total	5	17.5				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	9.506	0.259	36.727	0.000	8.787	10.225
Average Maintenance Time (hrs)	1.598	0.095	16.765	0.000	1.333	1.862

Figure 85. Medium TRUCC Regression Output

The derived equation is:

$$InventoryofTRUCCs = 9.51 + (1.598 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats.

9. Small TRUCC for Dumb LSF Threat

The minimum number of Small TRUCCs required in inventory to achieve an average of 15.0 TRUCCs on mission was 25. Table 48 only considers the required 15.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 48. Small TRUCC Maintenance Values

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
25	3.8	1	3.8	1	3.8	1
26	3.8	1.3	3.8	2	3.8	1
27	3.8	1.5	3.8	2	3.8	1
28	3.8	1.6	3.8	3	3.8	1
29	3.8	1.8	3.8	3	3.8	1
30	3.8	2	3.8	3	3.8	1

As depicted Table 48, maintenance times averaged 2 hours or less and averaged 1 hour for the worst-case scenario of only 10 spare TRUCCs in inventory. The data reveals that having a mean maintenance time of greater than 3 hours is not feasible without an additional 15 TRUCCs on station. The results also depict that having more than 28 TRUCCs in inventory contributes little added significance. The maximum combination was 3.8 hours of endurance with 2 hours of maintenance and the minimum combination was 3.8 hours of endurance with 1 hour of maintenance.

A regression analysis was performed on the data using the derived endurance time and the derived number of TRUCCs required on mission. As for previous variants, the model was only run until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. This model achieved an R-squared value of 0.98 and a p-value of near zero. The output from the regression is shown in Figure 86.

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.991					
R Square	0.983					
Adjusted R Square	0.978					
Standard Error	0.276					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	17.195	17.195	225.310	0.000115	
Residual	4	0.305	0.076			
Total	5	17.5				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	19.511	0.544	35.860	3.610E-06	18.000	21.021
Average Maintenance Time (hrs)	5.211	0.347	15.010	0.000115	4.247	6.174

Figure 86. Small TRUCC Regression Output

The derived equation is:

$$InventoryofTRUCCs = 19.51 + \left(5.21 \times AvgMainTime\right)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats, with an 98% chance that the number given will fall within a 95% confidence interval.

10. Small TRUCC for Smart LSF Threat

The minimum number of Small TRUCCs required in inventory to achieve an average of 13.0 TRUCCs on mission was 22. Table 49 only considers the required 13.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 49. Small TRUCC Maintenance Values

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
22	3.8	1	3.8	1	3.8	1
23	3.8	1.4	3.8	2	3.8	1
24	3.8	1.5	3.8	2	3.8	1
25	3.8	1.8	3.8	3	3.8	1
26	3.8	2	3.8	3	3.8	1
27	3.8	2	3.8	4	3.8	1

As depicted Table 49, maintenance times averaged 2 hours or less and averaged 1 hour for the worst case scenario of only 9 spare TRUCCs in inventory. The data reveals that having a mean maintenance time of greater than 7 hours is not feasible without adding 14 additional TRUCCs on station. The results also depict that having more than 25 TRUCCs in inventory contributes little added significance. The maximum combination was 3.8 hours of endurance with 4 hours of maintenance and the minimum combination was 3.8 hours of endurance with 1 hour of maintenance

A regression analysis was performed on the data using the derived endurance time and the derived number of TRUCCs required on mission. As for previous variants, the model was only run until the data met the required number of TRUCCs on station and the maximum maintenance time was observed. This model achieved an R-squared value of 0.94 and a p-value of 0.0015. The output from the regression is shown in Figure 87.

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.968					
R Square	0.937					
Adjusted R Square	0.922					
Standard Error	0.524					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	16.402	16.402	59.775	0.00151	
Residual	4	1.098	0.274			
Total	5	17.5				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	17.030	0.990	17.211	6.687E-05	14.283	19.778
Average Maintenance Time (hrs)	4.620	0.598	7.731	0.00151	2.961	6.280

Figure 87. Small TRUCC Regression Output

The derived equation is:

$$InventoryofTRUCCs = 17.03 + (4.62 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats.

11. Small TRUCC for ASCM Threat

The minimum number of Small TRUCCs required in inventory to achieve an average of 32.0 TRUCCs on mission was 49. Table 50 only considers the required 32.0 average TRUCCs in inventory, the average maintenance times required to support them, and minimum and maximum value combinations that could be used in order to meet the requirements.

Table 50. Small TRUCC Maintenance Values

TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (Hrs)	Max combination (Endurance/Maint Time) (Hrs)		Min Combination (Endurance/Maint Time) (Hrs)	
49	3.8	1	3.8	1	3.8	1
50	3.8	1	3.8	1	3.8	1
51	3.8	1	3.8	1	3.8	1
52	3.8	1	3.8	1	3.8	1
53	3.8	1	3.8	1	3.8	1
54	3.8	1	3.8	1	3.8	1
55	3.8	1	3.8	1	3.8	1

As depicted Table 50, maintenance times averaged 1 hour for all TRUCC inventory levels. The data reveals that having a mean maintenance time of greater than one hour is not feasible without adding 22 additional TRUCCs on station. The results also depict that having more than 49 TRUCCs in inventory contributes little added significance. The maximum combination was 3.8 hours of endurance with one hour of maintenance and the minimum combination was 3.8 hours of endurance with one hour of maintenance

12. Analysis of Small TRUCCs

Following data collection, Small TRUCCs were grouped by numbers required in inventory, TRUCCs required on mission, and the average maintenance time factors. A similar regression analysis was conducted to determine the number of TRUCCs required in inventory. The analysis achieved an R squared value of 0.99 with acceptable p-values for the number of TRUCCs required on mission and the average maintenance time. The data used (see Table 51) and the regression summary output (see Figure 88) are shown.

Table 51. Maintenance Time for X Amount of TRUCCs

TRUCCs in Inventory	TRUCCs Required	Average Maintenance Time (hrs)
11	6	1
12	6	1.4
13	6	2.3
14	6	2.8
15	6	3.6
16	6	3.9
22	13	1
23	13	1.4
24	13	1.5
25	13	1.8
26	13	2
27	13	2
25	15	1
26	15	1.3
27	15	1.5
28	15	1.6
29	15	1.8
30	15	2
49	32	1
50	32	1
51	32	1
52	32	1
53	32	1
54	32	1
55	32	1

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.995					
R Square	0.990					
Adjusted R Square	0.989					
Standard Error	1.593					
Observations	25					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	2	5263.200	2631.600	1036.798	0.000	
Residual	22	55.840	2.538			
Total	24	5319.04				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.852	1.449	0.588	0.562	-2.153	3.858
TRUCCs Required	1.556	0.042	37.343	2.149E-21	1.470	1.643
Average Maintenance Time (hrs)	1.700	0.520	3.267	0.00353	0.621	2.779

Figure 88. Regression Output

The derived equation from the analysis is:

$$InventoryofTRUCCs = .852 + (1.557 \times NumberofTRUCCsRequired)(1.699 \times AvgMainTime)$$

This equation yields the number of TRUCCs required in inventory for a given scenario with given threats.

G. ANALYSIS OF THE EFFECT OF OPERATIONAL AVAILABILITY ON THE TRUCCS

As previously stated, the critical assumption is that the TRUCCs deploy with a total system reliability of 0.95. Since reliability is less than 1, the 0.05 probability (1–0.95) that the system will fail must be accounted for; therefore, a binomial probability calculation was performed on each TRUCC variant for each mission. A binomial distribution was used in order to ensure that each TRUCC was treated independently. The equation used to calculate the TRUCCs probability of mission completion was

$$P_{MissionSuccess} = \sum_{i=k}^{n} \left[\frac{n!}{i!(n-i)!} \right] \times P_{reliability}^{i} \left(1 - P_{reliability}\right)^{n-i}$$ where n is the number of trials, k is the number of TRUCCs required for mission success, and $P_{reliability}$ is the reliability of the TRUCC.[91] The following tables and descriptions will illustrate the impact that the number of extra TRUCCs have on the probability that the minimum number of TRUCCs required will be available throughout the entire mission.

Table 52. Large TRUCC probability of mission completion

	LARGE								
SCENARIO	Required on Mission	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success
SMART LSF	3	3	0.857	4	0.987	5	0.999	6	0.9999
DUMB LSF	3	3	0.857	4	0.987	5	0.999	6	0.9999
SMART FAC/FIAC	3	3	0.857	4	0.987	5	0.999	6	0.9999
DUMB FAC/FIAC	3	3	0.857	4	0.987	5	0.999	6	0.9999
DUMB ASCM	3	3	0.857	4	0.987	5	0.999	6	0.9999

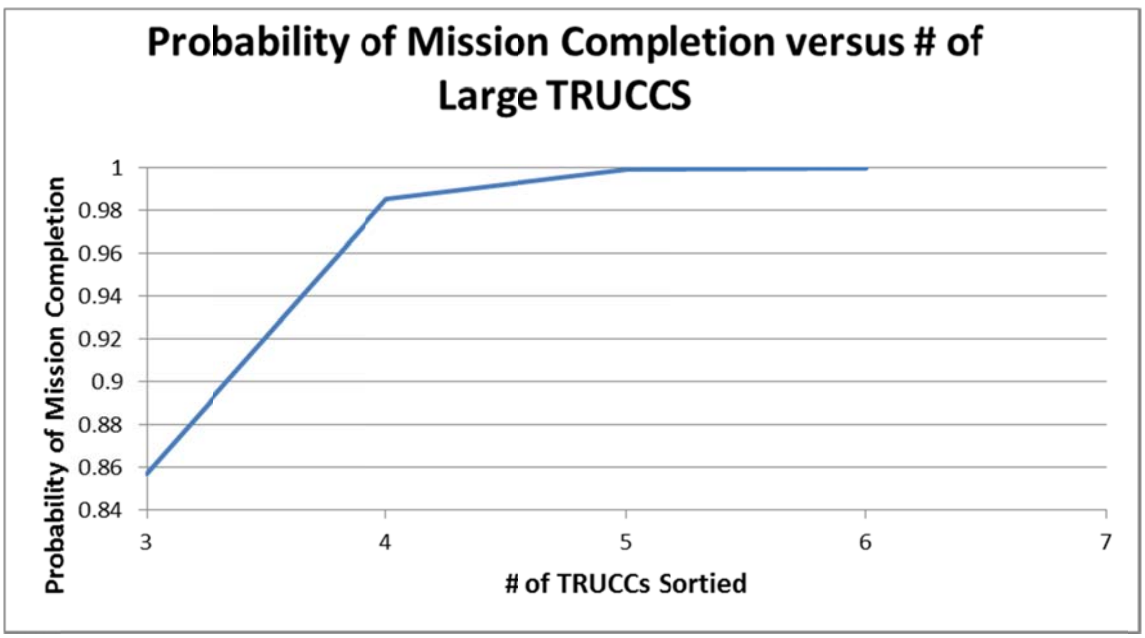

Figure 89. Probability of Mission Completion vs. Number of Large TRUCCs

91 (Hayter, 2012, p. 198)

Figure 89 reveals the potential for a significant increase in the probability of having the required TRUCCs throughout the given mission when considering the addition of one spare; a 13% increase in probability of mission completion for one additional spare and only a 1.2% increase when adding a second spare. The results show no significant benefit of having more than two spares.

Table 53. Medium TRUCC Probability of Mission Completion

	MEDIUM										
SCENARIO	Required on Mission	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success
SMART LSF	12	12	0.5404	13	0.865	14	0.97	15	0.995	16	0.999
DUMB LSF	7	7	0.6983	8	0.9428	9	0.992	10	0.999		
SMART FAC/FIAC	3	3	0.857	4	0.987	5	0.999	6	0.9999		
DUMB FAC/FIAC	3	3	0.857	4	0.987	5	0.999	6	0.9999		
DUMB ASCM	14	14	0.4877	15	0.829	16	0.957	17	0.991	18	0.999

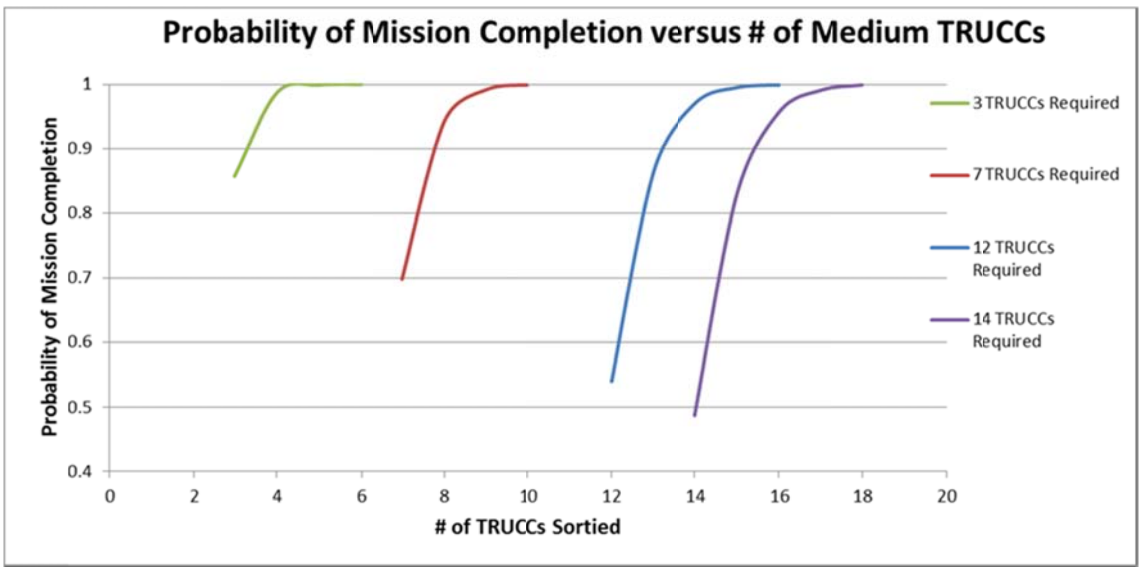

Figure 90. Probability of Mission Completion vs. # of Medium TRUCCs

Figure 90 also reveals the potential for a significant increase in the probability of having the required TRUCCs throughout the given mission when considering the addition of spares. This increase in probability of mission completion ranges from 13% to 34%. Adding a single spare TRUCC has a greater impact when the number of required TRUCCs is high. There is no significant benefit of having more than two spares when the number of TRUCCs required is less than 12.

Table 54. Small TRUCC Modeling Results

	SMALL												
SCENARIO	Required on Mission	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success	Availability	Probability of Success
SMART LSF	13	13	0.5133	14	0.847	15	0.964	16	0.993	17	0.999		
DUMB LSF	15	15	0.4633	16	0.8108	17	0.95	18	0.99	19	0.999		
SMART FAC/FIAC	6	6	0.7351	7	0.9556	8	0.994	9	0.999				
DUMB FAC/FIAC	6	6	0.7351	7	0.9556	8	0.994	9	0.999				
DUMB ASCM	32	32	0.1937	33	0.5037	34	0.759	35	0.904	36	0.968	37	0.99

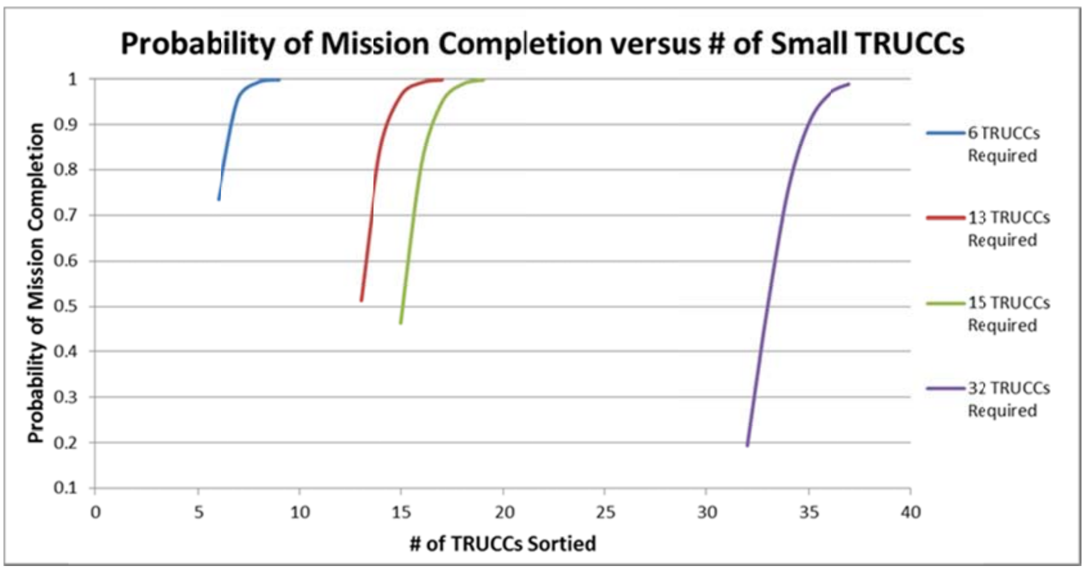

Figure 91. Probability of Mission Completion vs. Number of Small TRUCCs

As previously shown, Figure 91 reveals that there is the potential for a significant increase in the probability of having the required TRUCCs throughout the given mission when considering the addition of one spare. This increase in probability of mission completion ranges from 22% to 34%; 34% when 15 TRUCCs are required. There is no significant benefit of having more than two spares when the number of required TRUCCs is less than 13. However, it does show that there is still a significant increase in probability when the number of

TRUCCs required is 32 and continues to be significant up until there are four spares. One important takeaway from this data is that it shows that the benefit of spares begins to decrease between the requirement for 15–32 TRUCCs.

H. SENSITIVITY ANALYSIS

Start-up operational availability of the TRUCCs was fixed at 0.8 and only effects of maintenance and repairs investigated. A subsequent sensitivity analysis conducted on the operational availability for the TRUCCs prior to heading out on mission revealed operational availability ranges between 0.6 and .9 for the scenario of medium TRUCCs versus a smart LSF. Table 55 shows the results.

Table 55. Complete Ao Figures

Operational Availability	TRUCCs in Inventory	Average Endurance Time (Hrs)	Average Maintenance Time (hrs)	Max combination (Endurance/Maint Time)		Min Combination (Endurance/Maint Time)	
0.9	15	99.8	6.6	99.8	6.6	99.8	6.6
0.9	16	99.8	23	99.8	46.4	99.8	6.6
0.9	17	99.8	32.1	99.8	59.6	99.8	6.6
0.9	18	99.8	32.8	99.8	59.6	99.8	6.6
0.8	17	99.8	9.2	99.8	13.2	99.8	6.6
0.8	18	99.8	19.7	99.8	33.1	99.8	6.6
0.8	19	99.8	30.4	99.8	59.6	99.8	6.6
0.8	20	99.8	32.4	99.8	59.6	99.8	6.6
0.7	19	99.8	6.6	99.8	6.6	99.8	6.6
0.7	20	99.8	9	99.8	13.2	99.8	6.6
0.7	21	99.8	19.1	99.8	39.7	99.8	6.6
0.7	22	99.8	23	99.8	46.4	99.8	6.6
0.7	23	99.8	29.1	99.8	59.6	99.8	6.6
0.6	21	99.8	6.6	99.8	6.6	99.8	6.6
0.6	22	99.8	8.5	99.8	13.2	99.8	6.6
0.6	23	99.8	11.2	99.8	19.9	99.8	6.6
0.6	24	99.8	12	99.8	19.9	99.8	6.6
0.6	25	99.8	14.3	99.8	26.5	99.8	6.6
0.6	26	99.8	20.3	99.8	46.4	99.8	6.6
0.6	27	99.8	22.8	99.8	46.4	99.8	6.6
0.6	28	99.8	23.5	99.8	53	99.8	6.6
0.6	29	99.8	25.7	99.8	53	99.8	6.6
0.6	30	99.8	25.9	99.8	53	99.8	6.6
0.6	31	99.8	27.7	99.8	59.6	99.8	6.6
0.6	32	99.8	28.3	99.8	59.6	99.8	6.6
0.6	33	99.8	29	99.8	59.6	99.8	6.6

As depicted, start-up Ao has a significant impact on the number of TRUCCs required in inventory. The relationship between Ao and TRUCCs in inventory is inversely proportional; as Ao decreased, the amount of TRUCCs required in inventory increased. For every 0.1 decrease in Ao, the minimum amount of TRUCCs required increased by two. However, as the Ao decreased, achieving higher average maintenance times became difficult. Figure 91 shows the trend average maintenance times compared to the number of TRUCCs required in inventory for various start-up operational availabilities.

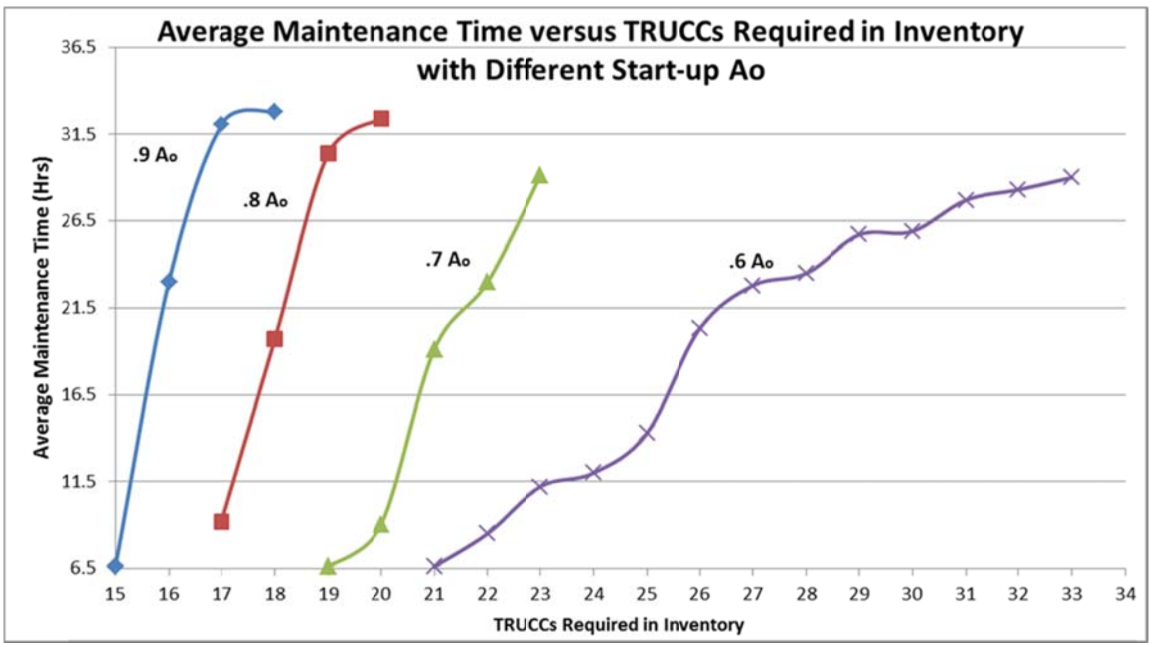

Figure 92. Average Maintenance Time vs. TRUCCs Required in Inventory for Different Operational Availabilities

Figure 92 clearly shows that as operational availability decreased, the number of TRUCCs significantly increased when compared to the average number of maintenance hours. This passes the common sense check: The TRUCCs require more repairs as Ao decreases and the time to repair increases as the number of available TRUCCs decrease. Achieving an operational availability of 0.8 on a vessel is difficult for today's equipment. One example of what today's leaders determine adequate operational availability to be represented by the Los Angeles Class Nuclear Powered Submarine (SSN). These extremely well-built and technically advanced vessels only achieve an operational availability of only 0.6. Other examples are the forward deployed Coastal Patrol Craft (PC), Ohio Class Nuclear Powered Submarines (SSBN), and forward deployed Guided Missile Destroyers (DDG). These vessels have calculated operational availabilities of 0.62, 0.68, and 0.2 respectfully. All of which are well short of the 0.8 that used for this report's analysis, however these systems of systems are more complex than the required for TRUCC. The LA class SSN is a very complex system of systems and its comparison is testament to the requisite advance of reliable technology inherent to the successful implementation of the TRUCC into fleet operations.

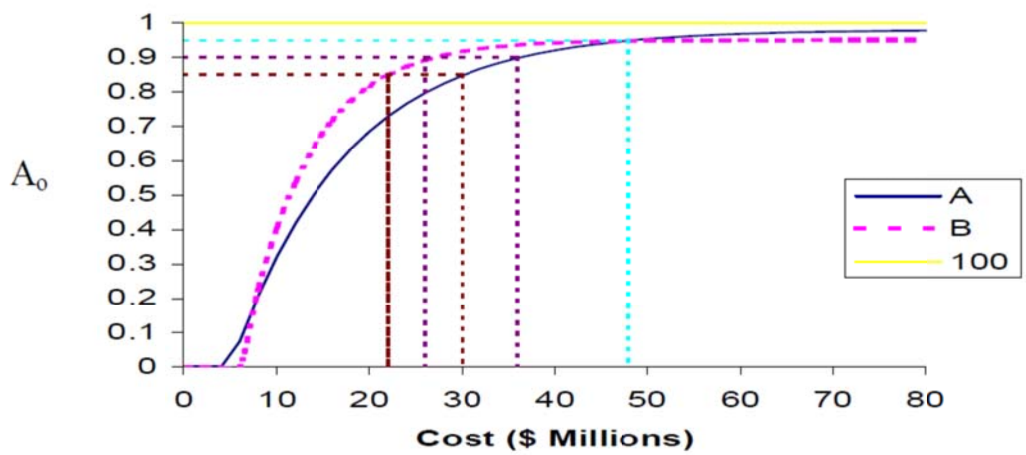

Figure 93. Cost of Varying Ao Values

I. COST OF OPERATIONAL AVAILABILITY

Figure 93 from OPNAVINST 3000.12A represents the cost of attaining different values of Ao. These data are from 2003 and compare fictitious systems, but adequately illustrate that each system has an Ao curve and no two systems cost the same when trying to obtain a certain value. Therefore, further analysis is required for each size variant of TRUCC before assigning a dollar figure associated with attaining the 0.8 Ao mark.

A regression analysis was conducted on the data collected to determine the weight of influence of Ao had in determining the number of TRUCCs required in inventory. The regression analysis took into account 26 data points for average maintenance time, operational availability, and the number of TRUCCs required in inventory. Achieving an R squared value of 0.88 with p-values for Ao and average maintenance time essentially zero shows that the data for maintenance times and Ao are important in determining the number of TRUCCs required in inventory. The output from the regression is shown in Figure 94:

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.939					
R Square	0.882					
Adjusted R Square	0.871					
Standard Error	1.871					
Observations	26					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	2	599.364	299.682	85.643	2.2019E-11	
Residual	23	80.482	3.499			
Total	25	679.846				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	45.771	2.342	19.545	7.980E-16	40.927	50.616
Operational Availability	-40.771	3.309	-12.322	1.300E-11	-47.616	-33.927
Average Maintenance Time (hrs)	0.272	0.042	6.487	1.281E-06	0.185	0.359

Figure 94. TRUCC Regression Output

The derived equation is

$InventoryofTRUCCs = 45.77 - (40.77 \times OpAvail) + (.272 \times AvgMainTime)$. This equation yields the number of TRUCCs required in inventory for a given scenario with given threats, with an 88% chance that the number given will fall within a 95% confidence interval.

J. CONCLUSION

Considering the aforementioned assumptions, the analysis yielded several conclusions. First, the average maintenance times have a significant effect on the number of TRUCCs required in inventory; maintenance times increased as the number of TRUCCs increased. A Poisson distribution represents the variations of the time to perform maintenance for this initial look at TRUCC maintenance. Detail-level design and specification will lead to a more thorough examination of the most appropriate distribution and mean maintenance time for the given system-of-systems, allowing a more precise analysis. Second, the number of TRUCCs required in inventory and the amount of time required for maintenance is greatly influenced by the level of Ao achieved; the number of TRUCCs required increased and it became increasingly difficult to accommodate long maintenance times as Ao decreased.

XIV. MISSION VEHICLE TECHNICAL COMPENDIUM

The Mission Vehicle sub-group was tasked with creating a vehicle for the mission based on the capabilities required to successfully complete the mission. Using the ship synthesis method and validating the approach using basic naval architecture principles, the purpose was to balance the design in an engineering perspective and calculate objective attributes for a given set of design variable values. Ship synthesis is essentially a technique to allow the development of a ship definition with the limited data available at the early stage of design[92]. The goal of the model was to use fixed mission parameters such as speed, total displacement, and type of hull and return capabilities and figures that were useful to other groups for further analysis. The group considered a monohull due to the vast ships in existence using this hull form, low technological risk, suitability in the littoral environment, and low speed requirement based on early screening experiments.

A. INPUTS AND OUTPUTS

A functional decomposition was the first step in assessing what the model was supposed to do. This led to a list of inputs and outputs. These outputs were used to derive the necessary inputs; starting with the desired outputs was a logical step since the Mission Vehicle group served as an integration point to the other groups' models. Once the complete list of outputs was clearly understood, the group began investigating the primary and secondary inputs feeding the outputs. Various specific algorithms process inputs and generate outputs using regression and ship synthesis principles.

[92] (Choi, 2009, p. 14)

During the process of investigating inputs and outputs, the model was divided into three main categories:

- Performance
- Sensors
- Weapons

This simplified the research and developmental processes of deriving algorithms necessary to achieve the desired outputs. These three categories were naturally grouped to the outputs of our model. This is important because it becomes apparent that the discipline of Naval Architecture is complex. Due to this complexity, it is necessary to stress that this analysis is a first-order ship synthesis study. Additional detailed naval architecture design is necessary to refine these initial designs.

B. ASSUMPTIONS

Within this study there are three categories of vessels. These categories constrain dimensional and pragmatic constraints and vary from one to the next; small, medium, and large. While conducting initial ship synthesis we discovered these relationships and correlations when transitioning between thresholds of weight and length. The paradigms for each shifted slightly.

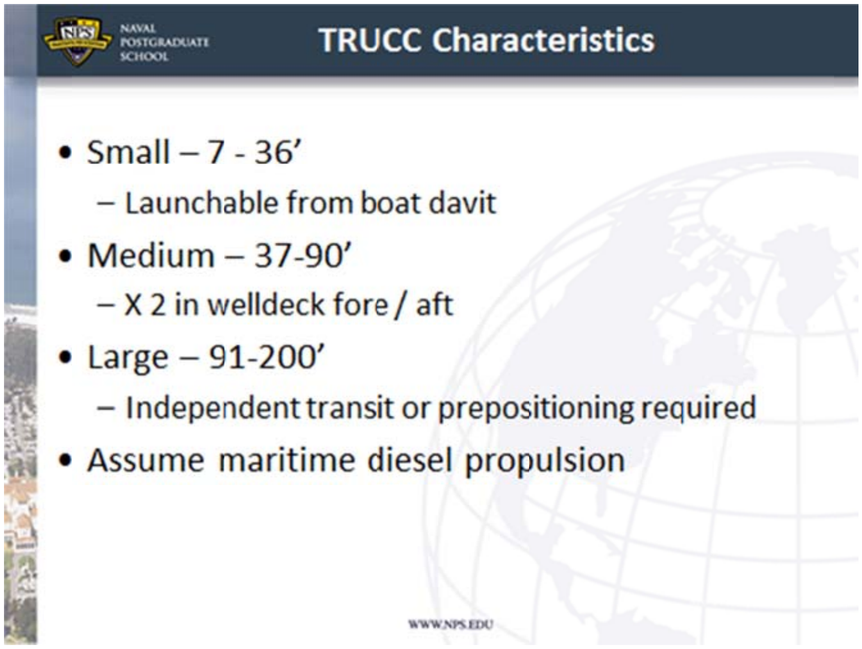

Figure 95. TRUCC Characteristics

Each size of TRUCC represents its manned counterpart's paradigm with the exception of arming. The TRUCCs have the characteristics featured in Figure 95. The arming shifts because you are now able to place directional launch missiles onboard TRUCCs similar in size to PCs, due to the absence of humans and exposure to the dangers of close proximity missile launches. Figure 96 illustrates arming paradigm for the TRUCC.

Figure 96. Arming Paradigm for TRUCC

Since personnel will be absent during TRUCC missions, weapons systems not usually on manned vessels can be placed on these TRUCCs. Figure 97 through figure 99, illustrate two vessels, one manned and the other unmanned with the same physical dimensions.

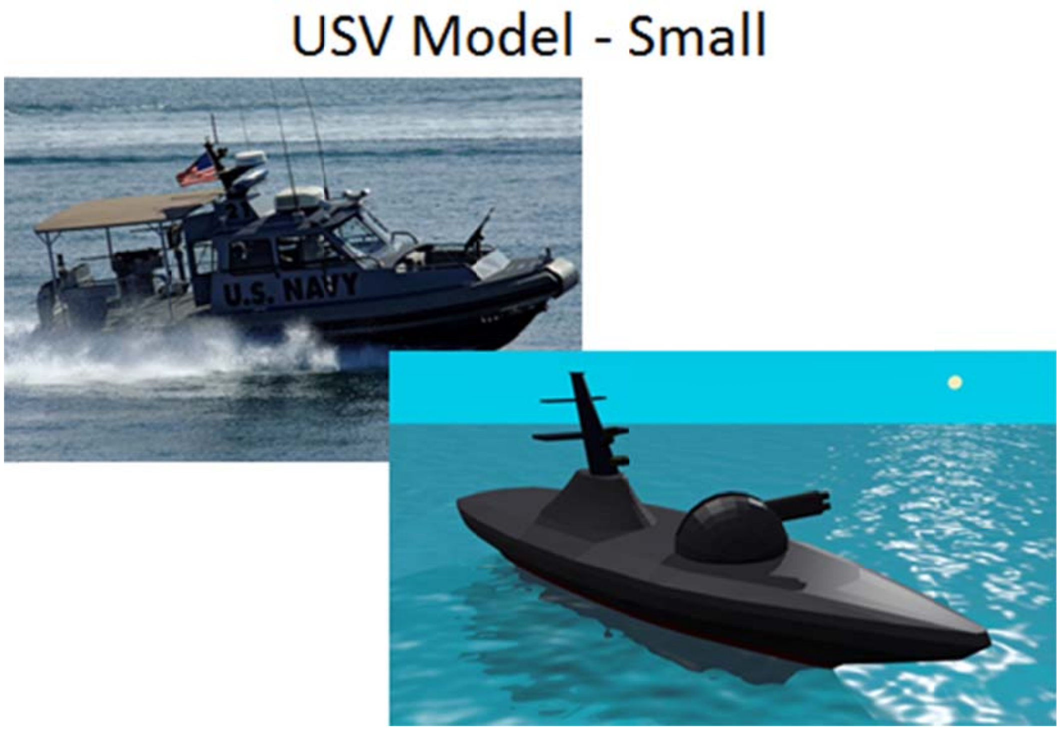

Figure 97. Dauntless Class Patrol Boat and Small TRUCC

1. Small TRUCCs

vii. Length to Beam Ratio is equal to or approximately 3:1

viii. Beam to Draft ratio is equal to or approximately 2:1

ix. Length ranges from 6 to 36 feet (+/- 20%)

x. Small caliber weapons

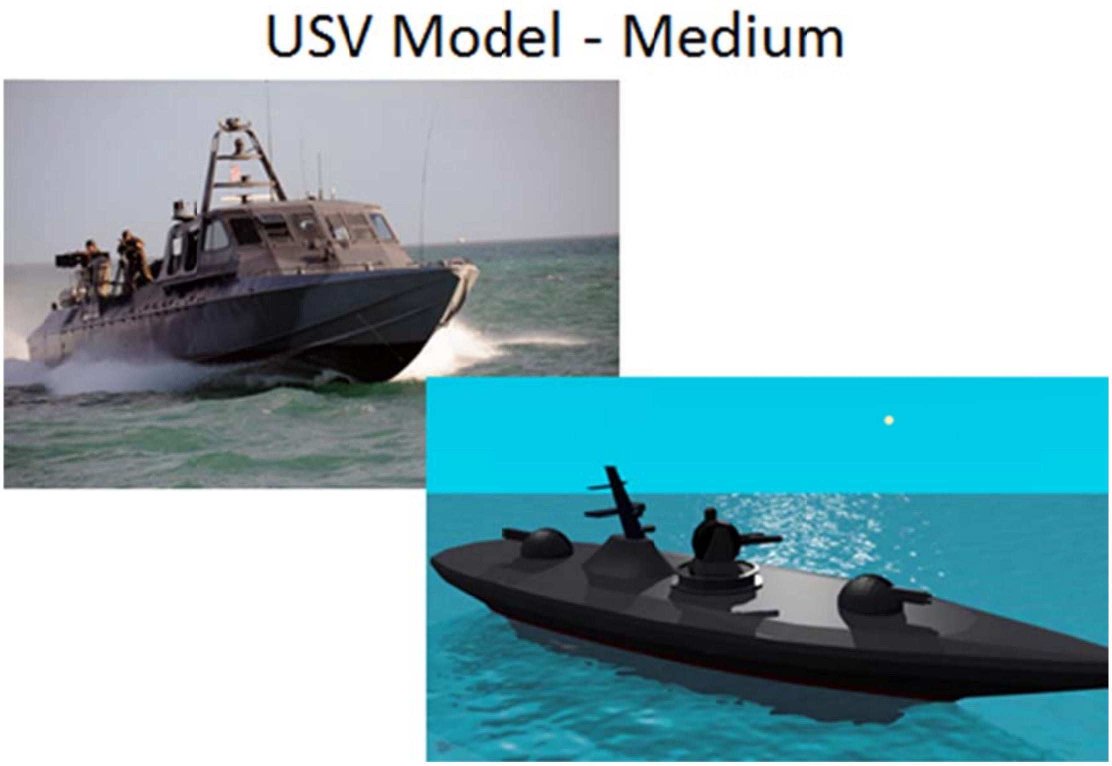

Figure 98. MK V Seal Vessel and Medium TRUCC

2. Medium TRUCCs

xi. Length to Beam Ratio is equal to or approximately 4.1:1

xii. Beam to Draft ratio is equal to or approximately to 3.1:1

xiii. Length ranges from 37 to 90 feet (+/- 20%)

xiv. Small caliber weapons

xv. 1 Medium caliber weapon

Figure 99. Cyclone Class Patrol Craft and Large TRUCC

3. Large TRUCCs

xvi. Length to Beam Ratio is equal to or approximately 5.25:1

xvii. Beam to Draft ratio is equal to or approximately 3.125:1

xviii. Length ranges from 90 to 200 feet (+/- 20%)

xix. Small caliber weapons

xx. 1 Medium caliber weapon

xxi. Directional missile launcher

The specific fuel consumption (SFC) is comparable to diesel engines. All vessels researched utilized diesel engines. The average SFC for diesel engines and gas turbine engines were calculated.[93] Although the use of gas turbine engines surfaced during the research, they were typically on larger vessels and therefore discarded from further consideration.

The fuel weight of a vessel is a function of the design draft. The relationship is not linear and changes drastically with draft. An exponential curve to fit the data was determined using gathered fuel capacity-to-weight ratios from Jane's Fighting Ships. The required Horsepower (HP) is a function of displacement, speed and length of vessel. A simple regression analysis was conducted to establish an equation to estimate HP using information gathered from Jane's fighting ships.

The number of small and medium caliber weapons is a function of displacement, speed, and length of vessel. The length to beam ratio is a function of displacement, speed, and length of vessel. The beam to draft ratio is a function of displacement, speed, and length of vessel. The fuel intake rates are a function of displacement, speed, and length of vessel.

The missile systems are best utilized on large ship due to weight and dimension requirements. Rolling Airframe Missiles (RAM) and Evolved Sea Sparrow Missiles (ESSM) are two missile system choices for large vessels. These are representative systems. The radar range equation determines the sensor range as a function of ship size.[94]

C. SHIP SYNTHESIS MODEL

1. Weapons

To derive the weapons characteristics of the vehicle, the current weapons paradigm for manned vessels was examined for vessels ranging in lengths from 7 to 200 feet. This revealed that weapons systems could be divided into three different types: small caliber weapons, medium caliber weapons and missiles. In

93 (Dalakos, 2011)

94 (Harney, Combat Systems Vol. 2, 2005, p. 155)

terms of capability, these terms translate to Low Mass, Low Pk (Small caliber), Medium Mass, Low Pk (Medium), Large Mass, High Pk (Missile).

a. Small caliber – Using historical systems to derive the amount of small caliber weapons to place onboard yielded the following ratio of weapons to length: for every 12.7 feet of length, there will be 1 small caliber weapon, see table 1. The representative weapons system for small caliber munitions was the GAU-19 machine gun. This is depicted in Table 56.

Table 56. Historical Data for Small and Medium Length Vessels

Historical Small and Medium Length Boat systems									
	Length (ft)	Beam (ft)	Weight (LT)	Speed (kts)	Horsepower (HP)	Small Cal. Wpn (SCW)	Length to Beam	W/S	Length to SCW
34 ft PB	34.00	12.00	9	36	740	4	2.83	2.25	8.50
Riverine Command Boat	49.00	12.40	23	40	850	3	3.95	7.60	16.33
Riverine PBF	39.37	19.03	10	38	440	3	2.07	3.33	13.12
Riverine Assualt Boat	33.14	8.86	9	40	440	5	3.74	1.80	6.63
27 ft PB	26.90	8.01	3	34	260	4	3.36	0.75	6.73
28 ft PB	27.89	9.84	6	38	500	4	2.83	1.50	6.97
Point Class	25.30	5.20	66	23	1600	2	4.87	33.00	12.65
Light Patrol Boat	22.31	8.53	1	35	300	4	2.62	0.25	5.58
Harbour Security Craft	24.00	8.00	4	22	330	1	3.00	3.90	24.00
NSW 11M RIB	36.09	10.50	9	35	940	2	3.44	4.50	18.05
MK V	81.04	17.39	55	45	4506	10	4.66	5.50	8.10
Riverine Assualt LCPF	35.10	9.20	8	43	600	1	3.82	7.50	35.10
River Patrol Boat	35.00	9.30	7	38	600	8	3.76	0.93	4.38
Averages	36.09	10.64					**3.46**	**5.60**	12.78

b. Medium caliber – Utilizing the manned systems scheme and modifying to the unmanned systems paradigm (still under development a medium caliber weapon was placed on all medium class ships and above; a real-world analogy of this principle is placing a MK38 Mod 2 machine gun on a MK5 Boat, and placing one MK38s on a Patrol Craft. Table 57 contains the specifications of the representative systems.

c. Missiles – A directional launch missile system was placed on large sized vessels to accommodate the lack of space and weight for Vertical Launch Tubes. These missile systems still provide a good range and high single shot probability of kill (Pssk). The weights of the systems include launcher, fire control (guidance) and, missile magazine

Table 57. Reference Weapon Systems

Reference Systems						
	Max Effective Range (yds)	**P kill @ 1000 yds**	**P kill @ 500 yds**	**Pkill @ 100 yds**	**Firing Rate (rounds/min)**	**Weight (kg)**
Small Caliber						
12.7 mm GAU-19/A	1900	0.68	0.70	0.75	1300	355
M2HB	1960	0.76	0.79	0.82	70	38.1
Medium						
Mk 38 Mod 2	2700	0.80	0.83	0.89	180	1,042
20 mm CIWS	2000	0.99	0.99	0.99	400–1500	494.5
30 mm CIWS	2000	0.99	0.99	0.99	600–1200	322

Table 58. Reference Missile Systems

Surface-to-air missiles	Max Effective Range (yds)	P Kill @ 1000 yds	Fire Rate (seconds between	Weight (kg)
RIM-162 ESSM	20000	0.7	5	8200
RIM-116 RAM	10400	0.6	1	7310

2. Performance

The derivation of dimension algorithms to convert simple inputs of speed, hull parameters, and total displacement was required to obtain performance characteristics.

a. *Dimensions*

Total displacement was converted to derive, length, beam, draft, and mast height using a ship synthesis approach. Table 59 is an illustration of the work completed.

Table 59. Dimensions of TRUCC, with Displacement as Input

Adjusted Displ.	**237**	**tons**		Length	49.1	m	161.2	ft
L/B	5.250			Beam	9.4	m	30.7	ft
B/H	3.125			Draft	3.0	m	9.8	ft
p	1.025	tons/m^3		Height	18.7	m	61.4	ft
Cb	0.290							

Length to Beam (L/B), Beam to Mast Height (B/H) ratios change in their relationships based on the total displacement of the vessel. 150 Long Tons (LT) and 70 LT were used because research revealed inflection points in behavior for all factors at these thresholds. The next equation converts the weight to length. The ratios then allow for deriving the remaining equations. The ratios in Table 59 were derived using a series of if-then statements and regression equations.

Derived equations; Displ – Abbreviation for Displacement

- L/B = IF(Displ<150,IF(Displ>70,(0.015407*Displ+3),3),5.25)
- B/H = IF(Displ<150,IF(Displ>70,(0.015407*Displ+2),2),3.125)
- p is constant; 1.025 tons/m^3
- C_b (block coefficient) = IF(Displ<150, 0.223, 0.29)
- Length=((DISPL*(L/B^2)*B/H)/(C_b*P))^(1/3)
  +(0.2*((DISPL*(L/B^2)*B/H)/(C_b*P))^(1/3))

Algorithms were then tested against actual systems/ships. Figure 100 is a chart of the comparison.

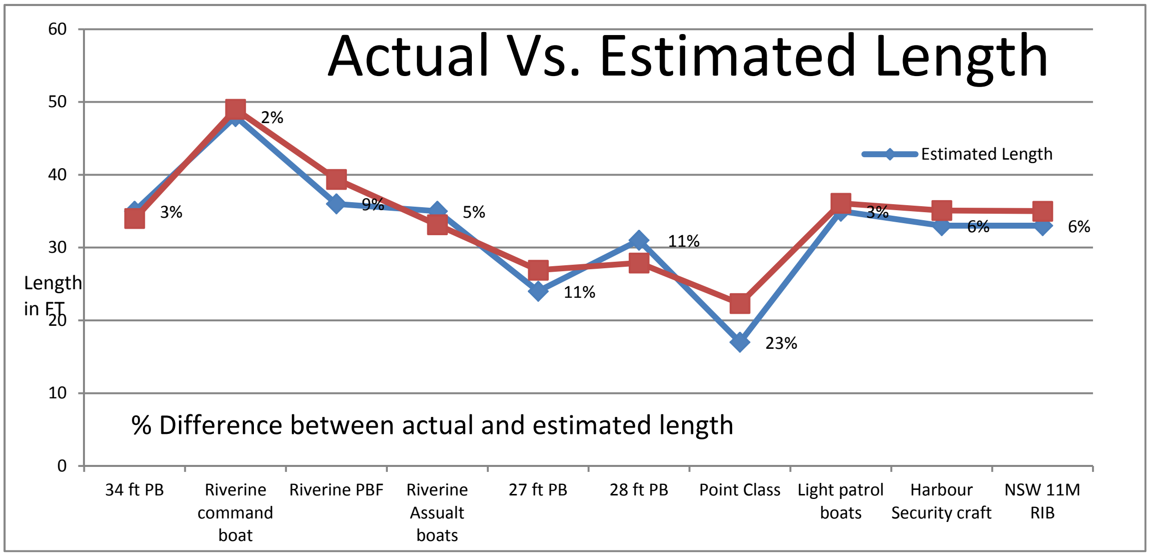

Figure 100. Actual Versus Estimated Length of TRUCC

These dimensions helped to place the design in perspective and allowed the group to pursue the remainder of the performance characteristics.

b. Horsepower

Estimated Horsepower (FT-LBS/Min) was derived via a regression.

- *Required HP* = IF(Length<120, HP Regression Equation, (2*Speed-Power*21.5))

HP Regression Equation = 242.2+20.2(Length)+3.8(Weight)-10.8(speed). A multivariate regression was used and the group conducted a multi-collinearity check. The group found multi-collinearity did not exist because *r* was not greater than or equal to 0.7; see Table 60.

Table 60. Multi-Collinearity Check

	HP	*Length*	*Weight*	*Speed*
HP	1			
Length	0.689	1		
Weight	0.670	0.647	1	
Speed	0.184	0.491	0.456	1

This equation was derived from historical systems in existence. Estimates were then compared to other systems/ships in existence. Figure 101 displays the results

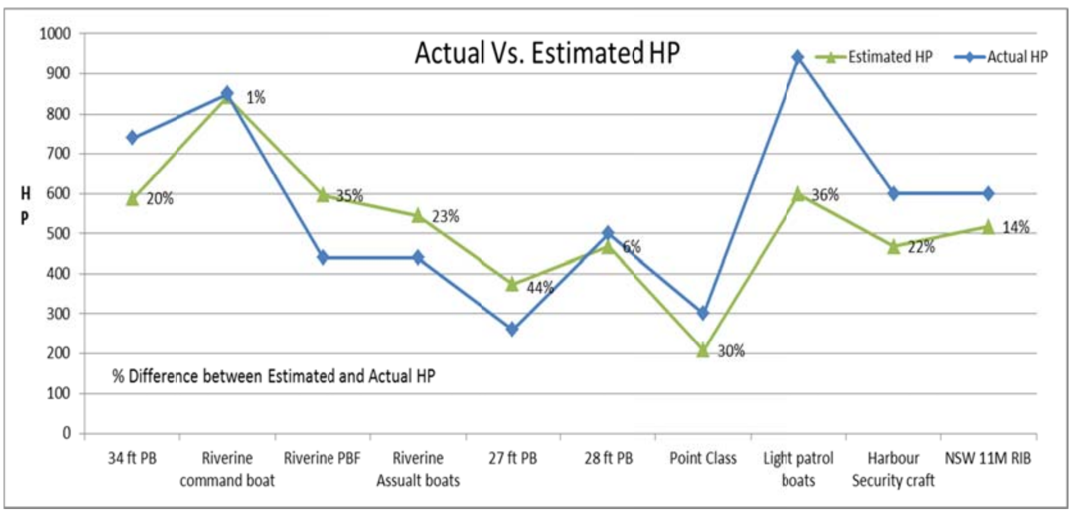

Figure 101. Actual versus Estimated Horsepower

c. Fuel Weight/Capacity

Fuel weight was the next important piece. The Fuel weight is determined by the fuel capacity which was derived from an exponential curve based on the historical data of ship's drafts, as per Figure 102.

- Fuel Capacity (gal) = 0.5*67.619*EXP(0.659*(Draft-2.15)) (Figure 102 refers)

- Fuel Weight (LT) = IF(Length<90, 0.075*(((Fuel Capacity)*7.01)/2240), ((Fuel Capacity)*7.01)/2240)

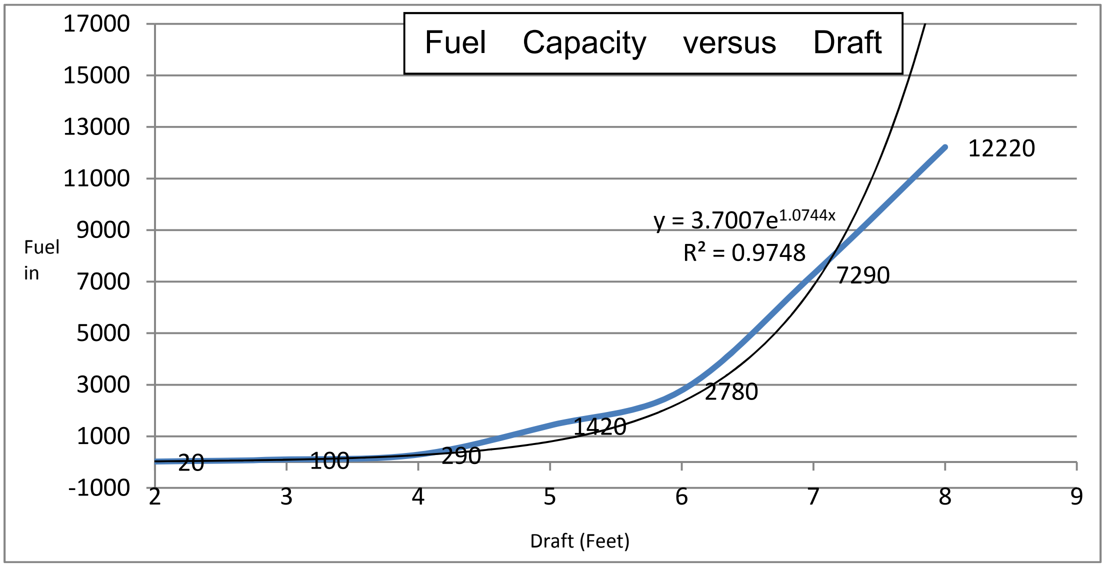

Figure 102. Fuel Capacity versus Draft Analysis

d. Endurance

Endurance was assumed to represent TRUCC operations in continuous use at max speed. Specific fuel consumption remain constant regardless of speed. Because this is the most restrictive, this errs on the side of caution for on-station time. In this model, the speed of this vessel does not change the SFC. The speed instead effects the endurance with a general estimation of cruise speed efficiency of assumed to be 70% of maximum speed. Required HP changes with speed of the vessel. In the accordance with the endurance relationship:

- Endurance = (1/(SFC*(Required HP/4)/Fuel Weight/2240)/.7)[95]

95 (Dalakos, 2011)

3. Sensors

The next area of focus was sensor performance. The weight of the sensor is not significant because today's conventional sensors can achieve the detection ranges required in the littoral DRMs. Initially, an attempt was made to place representative radar systems onboard the TRUCC keeping in mind weight requirements. The goal was to allocate a percentage of total displacement to sensor placement; however, this led to the detail level of Naval Architecture. Since most radars take up a fraction of the total displacement while still being able to see over the horizon, the model derived sensor performance from the simple radar range equation. It will be up to detail design to specify a sensor system that provides the range and sensor performance onboard a specific sized vehicle. For example, a Furuno surface search radar system weighs approximately 250 Kg, yet a SPY-1D system weighs several tons. Due to weight requirements, it is not feasible to place a SPY-1D system on the classes of ships in our analysis.

- Radar Range Equation = d(nm) = $1.23 * (\sqrt{H_{a(ft)}} + \sqrt{H_{t(ft)}})$

Ht is the Height of own-ship mast calculated from Table 59 which discusses dimensions.

Ha is the height of the target based on threat profile of the DRM. This is a value the user must input into the model initially. The probability of detection was fixed at 0.9 which is realistic and achievable with modern sensors against the given threat system

Table 61. Sensor Intermediate Output

Sensor			
Payload	Range of Detection	23297	yds
Payload	Probability of Detection	0.9	

D. SMALL UNMANNED SURFACE VEHICLE

Figure 103. Small TRUCC 6– 36 feet in Length

Table 62. Excel® Model Screen shot for Users; Small TRUCC

Hull Type		Monohull	1	*Output*	*MONOHULL*		
1		Catamaran	2	Weapons			
Mine Hunting Required ?	Yes or No	Triamaran	3	*Payload*	Missile	not capable	0
yes		M Hull	4		Maximum Effective Range	n/a	yds
					Probability of Kill	n/a	
User Inputs					Fire Rate	n/a	sec btwn shots
Speed		40	kts		Medium Caliber Weapon	Amount	0
Payload - Sensor			Long Tons		Maximum Effective Range	2700	yds
Payload - Weapon			Long Tons		Pk 1000	0.8	
Sea State					Pk 500	0.83	
Total Displacement		4	Long Tons		Pk 100	0.887	
Height of Target		200	ft		Fire Rate	180	rds/min
					Small Caliber Weapon	Amount	3
USV Specifications					Maximum Effective Range	1900	yds
Length		27	ft		Pk 1000	0.68	
Beam		9	ft		Pk 500	0.7	
Draft		4	ft		Pk 100	0.745	
Height		18	ft	*Payload*	Fire Rate	1300	rds/min
Horsepower		363	HP	Sensor			
Range at Max Speed		106	nm	*Payload*	Range of Detection	45200	yds
Range at Cruise Speed		152	nm	*Payload*	Probability of Detection	0.9	
Organic Asset	Unsupported	RMMV			Mine Range of Detection	n/a	yds
Length		23	ft		Probability of Detection	0.9	
Diameter		4	ft	Performance			
Vessel Definition		(+/-) 20 %		*Speed*	Cruise Speed	28	kts
Small		6-36 feet		*Speed*	Max Speed	40	kts
Medium		37-90 feet		*Range*	Endurance	3.8	hrs
Large		90-200 feet			Refuel Time	47	mins

E. MEDIUM UNMANNED SURFACE VEHICLE

Figure 104. Medium TRUCC 37 – 90 feet in Length

Table 63. Excel® Model Screen shot for Users; Medium TRUCC

Hull Type		Monohull	1
1		Catamaran	2
Mine Hunting Required ?	**Yes or No**	Triamaran	3
yes		M Hull	4
User Inputs			
Speed		40	kts
Payload - Sensor			Long Tons
Payload - Weapon			Long Tons
Sea State			
Total Displacement		68	Long Tons
Height of Target		200	ft
USV Specifications			
Length		69	ft
Beam		23	ft
Draft		11	ft
Height		46	ft
Horsepower		1398	HP
Range at Max Speed		2794	nm
Range at Cruise Speed		3992	nm
Organic Asset	**Unsupported**	RMMV	
Length		23	ft
Diameter		4	ft
Vessel Definition		(+/-) 20 %	
Small		6-36 feet	
Medium		37- 90 feet	
Large		90-200 feet	

Output	***MONOHULL***		
Weapons			
Payload	**Missile**	**not capable**	**0**
	Maximum Effective Range	n/a	yds
	Probability of Kill	n/a	
	Fire Rate	n/a	sec btwn shots
	Medium Caliber Weapon	**Amount**	**1**
	Maximum Effective Range	2700	yds
	Pk 1000	0.8	
	Pk 500	0.83	
	Pk 100	0.887	
	Fire Rate	180	rds/min
	Small Caliber Weapon	**Amount**	**6**
	Maximum Effective Range	1900	yds
	Pk 1000	0.68	
	Pk 500	0.7	
	Pk 100	0.745	
Payload	Fire Rate	1300	rds/min
Sensor			
Payload	Range of Detection	51500	yds
Payload	Probability of Detection	0.9	
	Mine Range of Detection	n/a	yds
	Probability of Detection	0.9	
Performance			
Speed	Cruise Speed	28	kts
Speed	Max Speed	40	kts
Range	Endurance	99.8	hrs
	Refuel Time	46	mins

F. LARGE UNMANNED SURFACE VEHICLE

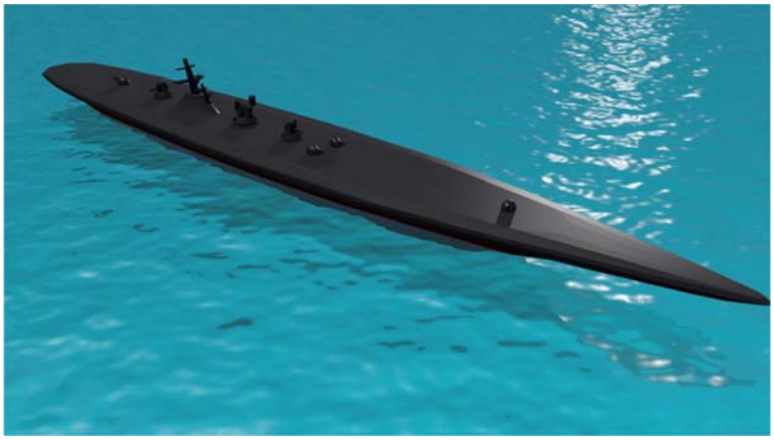

Figure 105. Large TRUCC 90 – 200 feet in Length

Table 64. Excel® Model Screen shot for Users; Large TRUCC

Hull Type		Monohull	1		***Output***	***MONOHULL***		
1		Catamaran	2		**Weapons**			
Mine Hunting Required ?	**Yes or No**	Triamaran	3		*Payload*	**Missile**	**missile capable**	**1**
yes		M Hull	4			Maximum Effective Range	20000	yds
						Probability of Kill	0.7	
User Inputs						Fire Rate	5	sec btwn shots
Speed		40	kts			**Medium Caliber Weapon**	**Amount**	**2**
Payload - Sensor			Long Tons			Maximum Effective Range	2700	yds
Payload - Weapon			Long Tons			Pk 1000	0.8	
Sea State						Pk 500	0.83	
Total Displacement		340	Long Tons			Pk 100	0.887	
Height of Target		200	ft			Fire Rate	180	rds/min
						Small Caliber Weapon	**Amount**	**15**
USV Specifications						Maximum Effective Range	1900	yds
Length		182	ft			Pk 1000	0.68	
Beam		35	ft			Pk 500	0.7	
Draft		11	ft			Pk 100	0.745	
Height		69	ft		*Payload*	Fire Rate	1300	rds/min
Horsepower		14620	HP		**Sensor**			
Range at Max Speed		2467	nm		*Payload*	Range of Detection	55300	yds
Range at Cruise Speed		3524	nm		*Payload*	Probability of Detection	0.9	
Organic Asset	**Supportable**	RMMV				Mine Range of Detection	Rng of Day	yds
Length		23	ft			Probability of Detection	0.9	
Diameter		4	ft		**Performance**			
Vessel Definition		(+/-) 20 %			*Speed*	Cruise Speed	28	kts
Small		6-36 feet			*Speed*	Max Speed	40	kts
Medium		37- 90 feet			*Range*	Endurance	88.1	hrs
Large		90-200 feet				Refuel Time	46	mins

APPENDIX A: LIST OF MISSIONS

Mission	Sub Mission	Mission	Sub Mission
Special Operations (SOF)	SOF Insertion Extraction	Logistics Support	Refueling Platform / Air
	Breaching		Refueling Platform / Surface
Navigation	Ice Breaking		Refueling Platform / Ground
	GPS Redundancy		Ammo Delivery
	AIS Monitor		Medical Resupply
Homeland Security	Crowd Control		Gen Purpose Retrieval/Delivery
	Border Patrol		Fire Fighting
	Commercial Inspection		PAX Transfer
Search and Rescue (SAR)	Search Platform		Port Services
	Recovery Platform		SAT Repair
	Casualty Extraction	Anti-Submarine Warfare	Threat Detection
	SAR Decoy		U/W Mine Delivery
	Human Remains Clearance		Threat Neutral
	Infrastructure Inspection	Anti-Surface Warfare (ASUW)	Threat Detection
Mine Warfare	Mine Layer		Threat ID
	Detect Mine		Threat Neutral
	Q-Route		MIO
	Mine Clearance		Drug Interdiction Ops
Intelligence, Surveillance,	Broad Area Surveillance		Anti-Piracy
and Reconnaissance	Positive Identification		Oil Platform Defense
	Reconnaissance	Electronic Warfare (EW)	EW C/M
	Early Warning		EW Attack
	Mission-Specific ISR		EW Detect
	Surface Search Coordination		EW Exploit
Command and Control	Info Relay		SIGINT
	Communications Relay	Explosive Ordnance Disposal (EOD)	IED Detection
	Radar Relay	Support	IED Clearance
	TACEMO		Land Mine Delivery
	Early Warning	Urban Warfare	Building Clearance
Force Protection	Harbor Patrol	Chemical, Biological, and Radiological	CBRN Detect
	Strait Security	(CBRN) Support	CBRN Survey
	Forward Base Security		CBRN Decon
	Under Water swimmer defense	Strike	Weapons Delivery
			Targeting
			BDA
			Air/Air Combat
			Directed Energy
		Meteorological	Mapping
			Bathymetric Collection
			Atmospheric Collection
			Disaster Monitor
			Resource Exploration

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APPENDIX B: PREDICTION EQUATIONS

Dumb ASCM Prediction Equation

$$
\begin{aligned}
&-27.989265671922 \\
&+0.3194609375 * \textit{Number of TRUCC} \\
&+0.00072815625 * \textit{Sensor Range} \\
&+0.00051334375 * \textit{Weapon Range} \\
&+26.661875 * \textit{Weapon Pk} \\
&+3.92892361111111 * \textit{Weapon Firing Rate} \\
&+(\textit{Number of TRUCC} - 40)((\textit{Sensor Range} - 10000) * -0.0000025890625) \\
&+(\textit{Number of \_TRUCC} - 40)((\textit{Weapon Pk} - 0.5) * -0.31596875) \\
&+(\textit{Number of TRUCC} - 40)((\textit{Weapon Firing Rate} - 5.5) * -0.02964409722222) \\
&+(\textit{Sensor Range} - 10000)((\textit{Weapon Range} - 10000) * -0.00000009564375) \\
&+(\textit{Weapon Pk} - 0.5)((\textit{Weapon Firing Rate} - 5.5) * -2.56986111111111)
\end{aligned}
$$

Dumb LSF Prediction Equation

$$
\begin{aligned}
&-22.774510604355 \\
&+0.3245703125 * \textit{Number of TRUCC} \\
&+0.00075896875 * \textit{Sensor Range} \\
&+0.00048590625 * \textit{Weapon Range} \\
&+25.908125 * \textit{Weapon Pk} \\
&+4.19829861111114 * \textit{Weapon Firing Rate} \\
&+(\textit{Number of TRUCC} - 40)((\textit{Weapon Firing Rate} - 5.5) * -0.00841840) \\
&+(\textit{Sensor Range} - 10000)((\textit{Weapon Range} - 10000) * 0.0000000982) \\
&+(\textit{Weapon Range} - 10000)((\textit{Weapon Pk} - 0.5) * -0.000101125) \\
&+(\textit{Weapon Pk} - 0.5)((\textit{Weapon Firing Rate} - 5.5) * -0.00005421)
\end{aligned}
$$

Smart LSF Prediction Equation

$$
\begin{aligned}
&-10.875215840841 \\
&+0.2941171875 * \textit{Number of TRUCC} \\
&+0.0598515625 * \textit{Speed of TRUCC} \\
&+0.00049321875 * \textit{Sensor Range} \\
&+2.06640625000002 * \textit{Sensor Detect} \\
&+0.00029009375 * \textit{Weapon Range} \\
&+23.9931249999999 * \textit{Weapon Pk} \\
&+3.61892361111111 * \textit{Weapon Firing Rate} \\
&+(\textit{Number of TRUCC} - 40)((\textit{Weapon Pk} - 0.5) * -0.16703125) \\
&+(\textit{Number of TRUCC} - 40)((\textit{Weapon Firing Rate} - 5.5) * -0.039019097222) \\
&+(\textit{Speed of TRUCC} - 30)((\textit{Sensor Detect} - 0.7) * -0.2349609375) \\
&+(\textit{Sensor Range} - 10000)((\textit{Weapon Range} - 10000) * -0.00000006404375) \\
&+(\textit{Sensor Range} - 10000)((\textit{Weapon Firing Rate} - 5.5) * -0.000050798611) \\
&+(\textit{Sensor Range} - 10000)((\textit{Weapon Firing Rate} - 5.5) * -0.0000484375) \\
&+(\textit{Weapon Pk} - 0.5)((\textit{Weapon Firing Rate} - 5.5) * -3.224583333333)
\end{aligned}
$$

Dumb FAC/FIAC Prediction Equation

$$
\begin{aligned}
&-34.220037429705 \\
&+0.5401015625 * \textit{Number of TRUCC} \\
&+0.00163024553571 * \textit{Sensor Range} \\
&+0.00689388586957 * \textit{Weapon Range} \\
&+305.856250000005 * \textit{Weapon Pk} \\
&+0.15890625 * \textit{Weapon Firing Rate} \\
&+(\textit{Number of TRUCC} - 40)((\textit{Sensor Range} - 1600) * -0.0001162667411) \\
&+(\textit{Number of TRUCC} - 40)((\textit{Weapon Range} - 1350) * 0.00005093070652) \\
&+(\textit{Sensor Range} - 1600)((\textit{Weapon Range} - 1350) * 0.00000494244953) \\
&+(\textit{Sensor Range} - 1600)((\textit{Weapon Pk} - 0.075) * -0.06840625) \\
&+(\textit{Sensor Range} - 1600)((\textit{Weapon Firing Rate} - 75) * -0.0000577276786) \\
&+(\textit{Weapon Pk} - 0.075)((\textit{Weapon Firing Rate} - 75) * -0.19275)
\end{aligned}
$$

Smart FAC/FIAC Prediction Equation

$$
\begin{aligned}
&-34.220037429705 \\
&+0.5401015625 * \textit{Number of TRUCC} \\
&+0.00163024553571 * \textit{Sensor Range} \\
&+0.00689388586957 * \textit{Weapon Range} \\
&+305.856250000005 * \textit{Weapon Pk} \\
&+0.15890625 * \textit{Weapon Firing Rate} \\
&+(\textit{Number of TRUCC} - 40)((\textit{Sensor Range} - 1600) * -0.0001162667411) \\
&+(\textit{Number of TRUCC} - 40)((\textit{Weapon Range} - 1350) * 0.00005093070652) \\
&+(\textit{Sensor Range} - 1600)((\textit{Weapon Range} - 1350) * 0.00000494244953) \\
&+(\textit{Sensor Range} - 1600)((\textit{Weapon Pk} - 0.075) * -0.06840625) \\
&+(\textit{Sensor Range} - 1600)((\textit{Weapon Firing Rate} - 75) * -0.0000577276786) \\
&+(\textit{Weapon Pk} - 0.075)((\textit{Weapon Firing Rate} - 75) * -0.19275)
\end{aligned}
$$

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